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Radio frequency scattering from a heated ionospheric volume, 2, Bistatic measurements

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A variety of bistatic experiments which were carried out for the purpose of determining the scattering properties of the heated inospheric volume in the F layer over Platteville, Colorado, are described. Results are presented on the basis of which it was first determined that the center-line scattering takes place from elongated field-aligned scattering structures. Measurements are presented showing that, for the center-line mode, the scattering of the incident signal consists, effectively, of specular reflections off the geomagnetic field lines.

1. INTRODUCTION

Observations of RF scattering from the heated ionospheric volume described in these papers included a number of bistatic measurements carried out directly in conjunction with backscatter experiments [*Minkoff et al.*, 1974]. As discussed in this reference, two scattering modes for the heated volume were observed: center-line scattering, in which, aside from small Doppler shifts due to ionospheric drift, the transmitted and received frequencies are the same; and plasma-line scattering, which appears as a pair of sidebands displaced on either side of the transmitted frequency by $\pm f_h$, where f_h is the HF heater frequency. Bistatic plasma-line scattering from the heated volume, in which VHF and UHF signals transmitted by the RAM radar at the White Sands Missile Range (WSMR) were received at the Stanford Research Institute radar near Palo Alto, California, are described by *Carpenter* [1974]. In what follows, only center-line scattering will be considered. These bistatic measurements had three major purposes: (1) to determine whether the scattering from the heated volume was, in fact, from field-aligned structures; (2) to determine whether the condition of perpendicularity between the radar line of sight and the earth's magnetic field, **B**, which was observed to be necessary for backscatter [*Minkoff et al.*, 1974; *Carpenter*, 1974], was representative of a more general situation in which the incident rays are specularly reflected off the magnetic field lines, with angle of reflection equal to angle of incidence; and (3) if it is assumed that the statistical properties of the electron density distribution are axially symmetric with respect to **B** then it can be shown [*Minkoff*, 1973] that the cross section for bistatic scattering axially around **B** is completely specified by the cross section for scattering within the plane containing **B**, and it should therefore be possible to predict received bistatic signal levels on the basis of backscatter measurements. The third major purpose of the bistatic measurements was to verify this experimentally. The experiments by which it was first discovered that the scattering in fact takes place from field-aligned structures are described in section 2. Experimental observations of specular reflections off **B** are described in section 3. Experiments for measuring axially-bistatic cross sections are described in section 4.

2. FIELD-ALIGNED STRUCTURES

The experiments of June 1971 involved backscatter measurements at VHF/UHF using the RAM radar at the White Sands Missile Range [*Minkoff et al.*, 1974], and HF backscatter measurements at 15 and 30 MHz [*Thome and Blood*, 1974]; the HF radars were located about 10 miles east of RAM (see Figure 1 in the paper by *Minkoff et al.* [1974]). It was at these HF wavelengths that remote backscatter from the heated volume was first observed during October 1970 [*Thome and Blood*, 1974]; the first observations of backscatter from the heated volume in the VHF/UHF range were made at RAM during the June 1971 experiments. These early HF results, however, gave no indication of the morphology of the scattering structures, that is, whether or not they in fact consisted of long columns of ionization aligned with the magnetic field. In order to determine this, the June 1971 experiments included a KC-135 aircraft operating as a mobile bistatic receiver platform for the RAM VHF/UHF signals (157.5 and 435 MHz) and the 15- and 30-MHz HF transmissions. The use of the aircraft for these experiments was provided by the Rome Air Development Center. The aircraft flight paths during the experiments consisted of north-south headings, between WSMR and Platteville, and east-west headings perpendicular to the north-south paths. Since the magnetic declination at Platteville is 13°, the north-south flight paths were very nearly within the magnetic meridian plane. The scattering produced by a field-aligned structure of length L is confined within a nominal angular range λ/L within any plane containing **B**, and has a very broad angular lobe measured azimuthally around **B**. Thus it is evident from Figure 1 of *Minkoff et al.* [1974] that, if the scattering in fact took place from field-aligned structures, the extent of the scattering zones over the ground as observed by the aircraft during the north-south flight paths would be quite narrow in comparison with their extent as observed during the east-west flights.

Positive results were obtained at 15, 30, and 157.5 MHz. However, because during the June 1971 experiments RAM could not radiate continuously, only the HF measurements were useful for these purposes; subsequent VHF aircraft experiments are described in section 3. An example of the results at 15 and 30 MHz is shown in Figure 1. Both o-mode and x-mode heating were employed. At all times, the scattering at 30 MHz was observed to be localized within regions about 200 km in extent in the north-south direction; the 15-MHz regions were somewhat broader and were located north of the 30-MHz zones. It was verified by means of ray-tracing calculations described in section 3 that this was due to refraction. For the east-west flight paths, strong signals at 15 and 30 MHz were recorded continuously over flights to points as far as 600 km to the west of the WSMR-Platteville heading, at which times the aircraft was forced to turn back because of

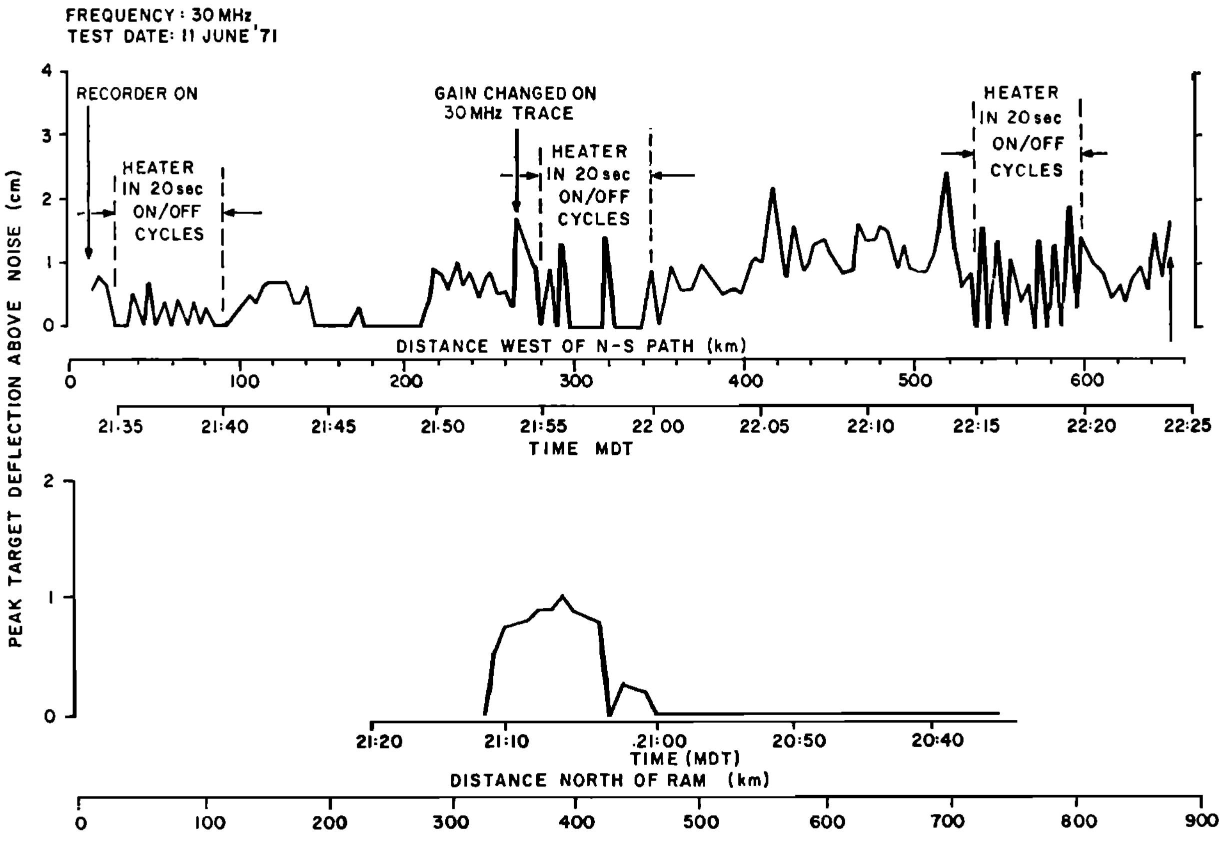

Fig. 1. Example of experimental results which first established presence of elongated field-aligned scattering structures within a heated volume. This follows from observed scattering zone during east-west flight (top) being much broader than zone observed during north-south flight (bottom).

lack of fuel; because of this the extreme westward limits of the scattering zones were never actually determined. No eastward flights were made but these would presumably have yielded similar results. From a comparison of the extents of the measured north-south and east-west scattering zones we conclude that the scattering takes place from elongated field-aligned structures.

The widths of the observed north-south zones are explained as follows. As discussed by *Minkoff et al.* [1974] for backscatter, the scattering takes place essentially along the perpendicularity contour, $C_\perp$, defined as the locus of points over which rays from the transmitter are perpendicular to **B**. Similarly, for bistatic scattering between any two given points in the meridian plane, there is also a contour over which all rays from the transmitter are scattered to the receiver. This contour is denoted as $C_{\bar{\gamma}}$ ($\bar{\gamma} = \pi/2 - \gamma$) where, at the point of intersection over the heater between the lines of sight from the transmitter and the receiver, γ is the angle between the lines of sight and the normal to **B**. All such contours must be essentially parallel, since otherwise an intersection between contours could take place which would require the angle of incidence between a single ray and **B** at a single point to be multivalued. Thus, for a fixed transmitter site, the set of all receiver sites defined by different values of γ corresponds to a set of parallel contours $C_{\bar{\gamma}}$ displaced from one another essentially in altitude. As the aircraft flies along the north-south path it therefore effectively scans through a continuous set of such contours, in which the overall altitude extent of the set is defined by the altitude extent of the scattering volume. Hence the width of the observed north-south scattering zone over the ground is dependent on the altitude extent of the ionospheric volume over which, as a result of the heating process, scattering at the particular wavelength of interest can take place. In addition, the finite beamwidth of each individual field-aligned structure, λ/L, also contributes to the width of the scattering zone and the net result consists of a convolution of the two effects. However, since we know for these experiments that $L > 85$ ft [*Minkoff et al.*, 1974], the scattering lobe width was relatively narrow, and the observed north-south extent of the scattering zones was therefore primarily determined by the altitude extent of the scattering region.

3. SPECULAR REFLECTIONS

An analysis of the aircraft data described in section 2 was performed in which ray-tracing calculations of the HF scattering zones for both 15 and 30 MHz were carried out for a time on 8 June during which the aircraft was receiving signals, and the results of the calculations were compared with the measurements; the electron density profile for this time period which was used in the calculation was provided by the Institute for Telecommunication Sciences (ITS). The calculation procedure was as follows. It was assumed that the heated volume was confined to a box extending 100 km north and south of the Platteville heater, with an altitude extending from 200 to 350 km. These values were chosen to correspond with ITS ionosonde measurements of heated-volume height [*Utlaut and Violette*, 1974], and HF backscatter pulse width measurements [*Thome and Blood*, 1974]. The calculation was two-dimensional, i.e., confined to the plane containing the flight path. Rays were traced from the HF antennas up into the assumed heated volume. The takeoff angles for the rays covered the vertical beamwidths of the antennas in one-deg increments, and the amplitude weighting imposed by the antenna gains was also taken into account. The altitude range of the volume was divided into 10-km increments. For each point of intersection between a transmitted ray and a 10-km altitude marker the ray-tracing program gave the corresponding ground range and angle of incidence to **B** at the point. A specular reflection off **B** was then assumed in which each ray was given an angle of reflection equal to the angle of incidence, and each ray was then traced back down through the ionosphere to the point where it intercepted an altitude of 10 km—the altitude of the aircraft during the flights. The computer output consisted of the value of the ground range to each such point. The final step consisted of dividing the flight path into 50-km increments, adding up the number of such points within each increment and constructing a histogram. These histograms are shown in Figure 2 overlaid on the measured values of relative power versus aircraft location as observed at this time. It is seen that, for both 15 (top) and 30 MHz (bottom), the calculation has clearly reproduced the location where the peak responses were observed. The calculated 15-MHz region is also seen to be located farther north than the 30-MHz zone, which, as noted above, is consistent with all the aircraft observations during this experiment. A more exact fit between measured and calculated results would no doubt be obtained by varying the assumed altitude extent of the scattering region and also by choosing a finer altitude grid within the heated volume. These cal-

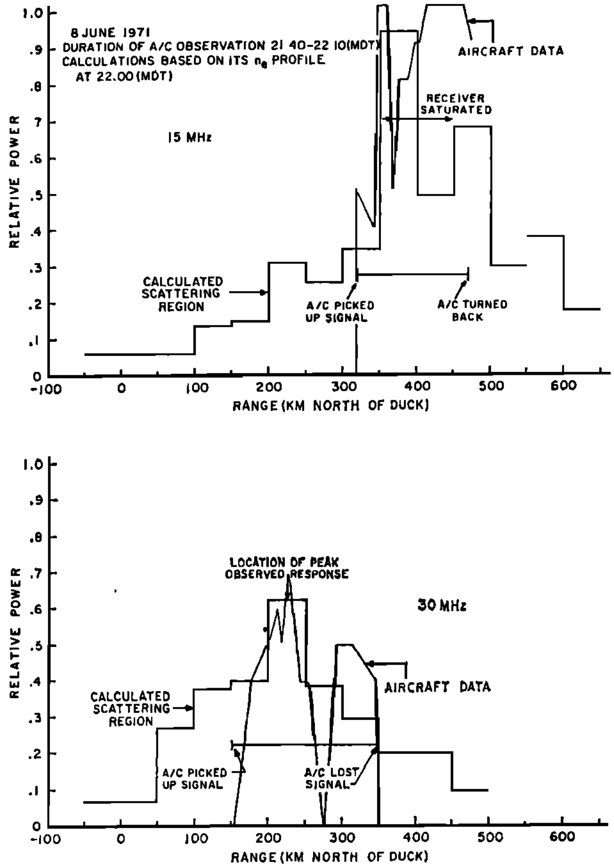

Fig. 2. Comparison of north-south scattering zones observed on 8 June on board aircraft (A/C) with results of the ray-tracing calculations. As indicated, the 15-MHz zone extends over a larger distance. This occurs because the altitude extent within the heated volume over which scattering actually takes place increases with wavelength because of the corresponding increase of the scattering cross section. Calculation has exactly reproduced observed region of maximum scattering. 15-MHz zone is northward of 30-MHz zone because of greater refraction at the lower frequency.

culations, however, provide strong evidence for a picture of the scattering process in which the rays are assumed to be specularly reflected off **B**.

A VHF aircraft experiment similar to that described in section 2 was carried out in February 1972, for which the north-south scattering regions are shown in Figure 3. Also presented for the times that the scattering was observed are the approximate values of signal-to-noise ratio (snr) of the signals received on board the aircraft, the maximum heating altitudes, h_f, where the heater frequency, f_h, is equal to the local plasma frequency f_p, and the nominal values of the elevation angles of the RAM antenna, which executed elevation scans periodically throughout these experiments. It is seen that the observed scattering regions fell northward for early times when the h_f values were relatively low, and gradually moved to the south as the day progressed and the reflection layer moved upward such that the conditions for direct backscatter at RAM improved. From these data, the southerly scattering zones corresponding to strong backscatter also appear to be broader than the regions located further to the north. Note that at approximately 19:02 the aircraft lost the signal at a range 220 nautical miles north of RAM when the RAM elevation angle was 15°. At this point an elevation scan was executed and the aircraft reacquired the signal for a RAM elevation angle of 10°. Thus it is also seen that when the aircraft was to the north, lower elevation angles were necessary in order for the scattering to be directed toward the aircraft's location. All these results are consistent with the notion of specular reflections from the magnetic field lines and, although the scattering region is evidently spread out in altitude extent, also show that the strongest reflections occur, as expected, in the vicinity of h_f, where the maximum heating is believed to take place.

All of these results deal with bistatic scattering essentially within the meridian plane. Out of the meridian plane we expect the scattering to consist of the locus of all specularly reflected rays which form a cone with **B** as the axis. For any given RAM elevation angle, the contour over the ground where maximum scattering should be observed consists of the intersection of the appropriate scattering cone with the surface of the earth. A set of such contours is presented in Figure 4, which also gives the h_f values for matching the heating altitudes to the altitudes above the heater corresponding to the different elevation angles. In April 1972 an aircraft experiment was carried out to determine whether the scattering in fact took place as predicted by this conical model. The aircraft flight path, denoted in the figure by the letters A through F, was designed to place the aircraft at locations out of the meridian plane where, for previously selected values of h_f and RAM elevation angles, strong scattering would be predicted by the model. Points where scattering was observed, denoted by the numbers 1 through 4, together with the snr values of the received signals and the h_f values for those observation times, are also shown. For the points indicated, the h_f values are seen to be close to their predicted values. During the initial portion of the flight the h_f values were kept between 240 and 270 km and scattering was observed at points 1 and 2. When the aircraft reached point B, the h_f value was lowered and maintained between 200 and 215 km. Although the geometry was therefore favorable for reception at the northern part of the BC leg, no scattering was observed on this path. However, this may have been due to system sensitivity since on the southward path, CD, the signals received at 3, where the range to the heated volume was somewhat less, were quite weak (2 to 3 db snr). On the third pass through the predicted scattering zone, along the leg DE, weak signals were again received (point 4). Measured values of time delays for points 3 and 4 are in good agreement with calculated values. At E, h_f was again set to 240 km. Scattering should have been observed on the path EF but was not, which is surprising in view of the reduced range. These results may therefore be summarized as follows. For all cases in which scattering was observed, the aircraft was in a region where scattering was predicted by the conical model. On the other hand, there were also cases where scattering was expected and was not observed. It is not known whether this is to be explained on the basis of a more complicated scattering model or equipment sensitivity and/or possible malfunction.

A similar experiment was carried out, at 157.5 MHz, for bistatic scattering from RAM to the Stanford Research Institute (SRI) radar near Palo Alto. The beamwidths of these radars at these frequencies are 5.2° and 3.0° respectively. It is found that, above the Platteville heater, for an 8° RAM elevation angle the line of sight makes an angle of incidence to B of 83.77°, and for a nearly horizontal beam position, the angle of incidence to B between the line of sight from the SRI radar is 83.87°. Thus for these elevation angles the lines of sight from RAM and the SRI radar are effectively on the same scattering cone, and maximum scattering at SRI should be observed. During the experiment the RAM antenna was scanned in elevation between 8° and 24° and the SRI elevation angle was held fixed. Some of the times at which maximum signals were received at SRI are given in Table 1 together with the recorded RAM elevation angles. It is seen that the results agree with predicted values to within 1° or 2° which is within the error of the known RAM elevation angle at the time of the experiment. Note also that the times between maxima are approximately 1.5 min which

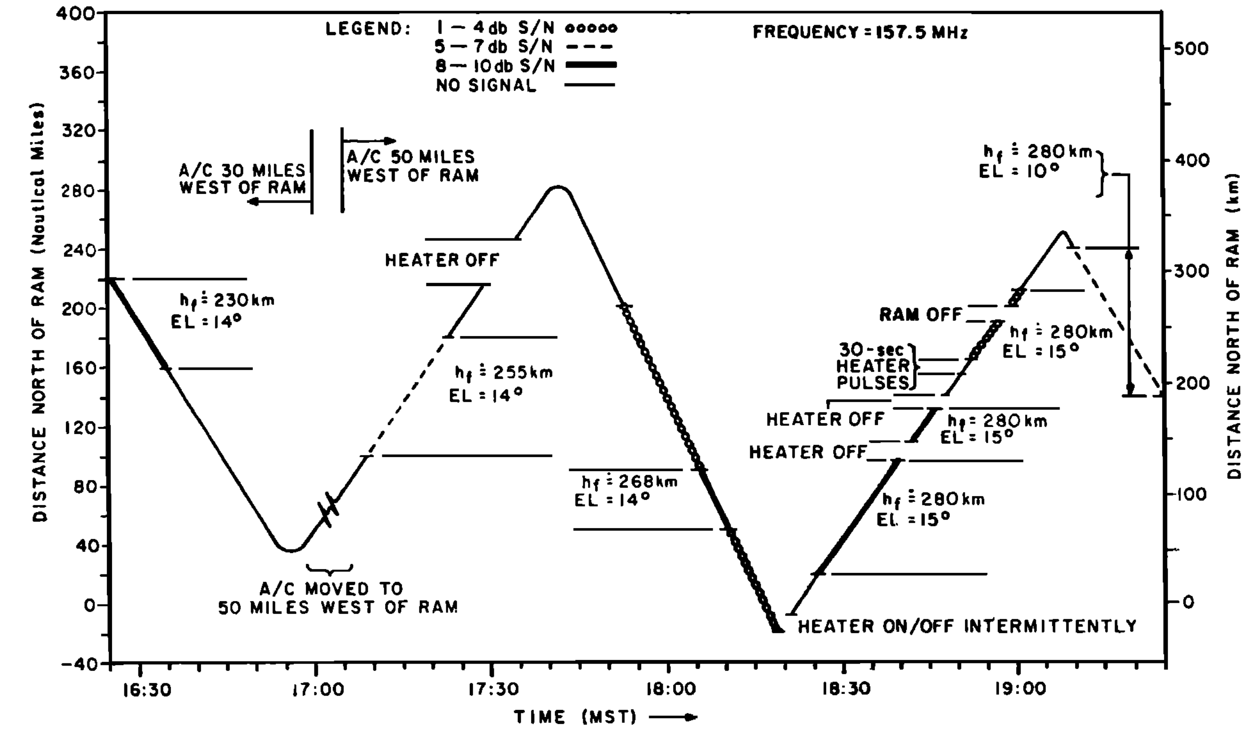

Fig. 3. Results of VHF aircraft (A/C) experiment demonstrating specular reflection of transmitted signal off B.

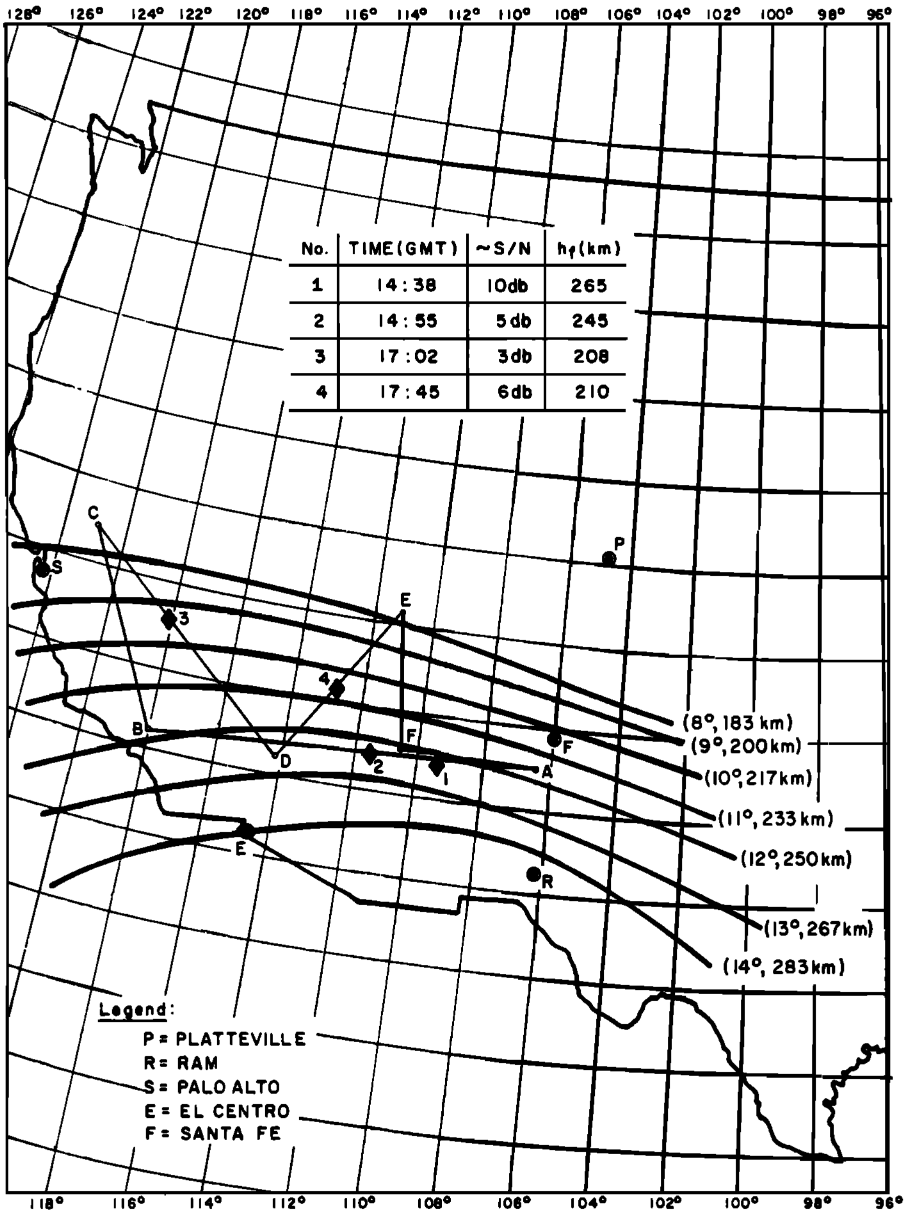

Fig. 4. Experimental aircraft results for verifying conical model for scattering out of meridian plane. Contours shown are calculated loci of maximum scattering for various RAM elevation angles; corresponding heater reflection heights, h_f, are also given. Aircraft flight path is denoted by letters A through F.

is in almost perfect agreement with the scan rate of the RAM antenna at this time. To summarize, all the results of this section are consistent with the conical model for the center-line scattering described above, in which the incident signal is specularly reflected off the magnetic field lines, the angle of reflection being equal to the angle of incidence.

4. BISTATIC CROSS SECTIONS

Experiments to verify that the cross section for bistatic scattering out of the meridian plane can be determined directly from measurements of backscatter vs. frequency within the meridian plane were carried out, in which VHF signals transmitted from RAM and scattered from the heated volume were

TABLE I. RAM-SRI bistatic measurements. Test date, 25 April 1972; frequency, 435 MHz.

Time (GMT)	RAM elevation angle (deg)
17:21:20	10
17:22:55	9
17:24:20	11
17:25:55	9
17:35:10	10
17:36:30	9
17:38:00	9
17:39:30	9
17:41:00	9
17:42:30	9
17:44:00	9

received at a fixed bistatic site at El Centro, California (see Figure 4). The analysis of these data is presented by *Minkoff* [1974] where it is seen that, for this relatively small axial bistatic angle ($3\pi/4$), there is good agreement between predicted and measured values.

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