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EXPERIMENTAL EVIDENCE OF A STRONG TE-POLARIZED WAVE FROM AN AIRBORNE LF TRANSMITTER

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Qualitative arguments are advanced to show that the nearly horizontal trailing-wire antennas of high-speed, high-altitude aircraft should excite waves of appreciable intensity in the Transverse Electric (TE) polarization. The altitude distribution of these waves should however differ markedly from that of the conventional Transverse Magnetic (TM) waves. To test these ideas, a special balloon receiver-probe was designed and flown. The experimental data provide strong evidence that TE fields from a standard ARC-96

20. Abstract (Continued)

airborne transmitter not only exist, but can be much larger than the associated TM fields at high altitudes.

Preface

The authors wish to thank MSgt John E. Bowers (Ret), MSgt Robert L. Evers (Ret) and MSgt Myron B. Deering (Ret) of the Aerospace Instrumentation Laboratory (AFCRL) and Sgt Richard R. Reed of the Upper Atmospheric Physics Laboratory (AFCRL) who assisted in the electronic instrumentation and data processing. We are also indebted to Mr. John L. Heckscher and Dr. Paul A. Kossey for many valuable contributions and especially to Dr. R. N. Ghose who originally stimulated our interest in the subject.

Contents

Illustrations

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Experimental Evidence of a Strong TE-Polarized Wave From an Airborne LF Transmitter

1. INTRODUCTION

Conventional Low-, and Very Low Frequency LF/VLF radio transmitting stations have vertical antennas which excite waves of Transverse Magnetic of "TM" polarization (Figure 1) in the earth-ionospheric waveguide. LF and VLF waves can also be transmitted from aircraft equipped with long trailing-wire antennas, but in the case of the Air Force ARC-96 system, air-drag causes the antenna wire to be nearly horizontal and the efficiency for radiating TM waves is severely reduced. The question therefore arises as to whether power radiated in the Transverse Electric polarization (Figure 2) can be used for communication purposes. The answer depends on the distribution of TE wave-intensity with altitude, azimuth, and range, as well as consideration of the background noise-fields, and the practicality of receiving antennas, etc.

As early as 1965, Ghose[1] considered the possibility of using a current-loop to excite TE-polarized waves in order to verify theoretically-predicted low attenuation rates. Ghose and Schwartz[2] discussed many features of TE wave propagation and conducted microwave scale-model studies supporting their calculations.

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[1] Ghose, R.N. (1965) Personal communication.

[2] Ghose, R.N., and Schwartz, K. (1965) Final Report, Contract No. AF33(615)-2216, American Nucleonics Corporation.

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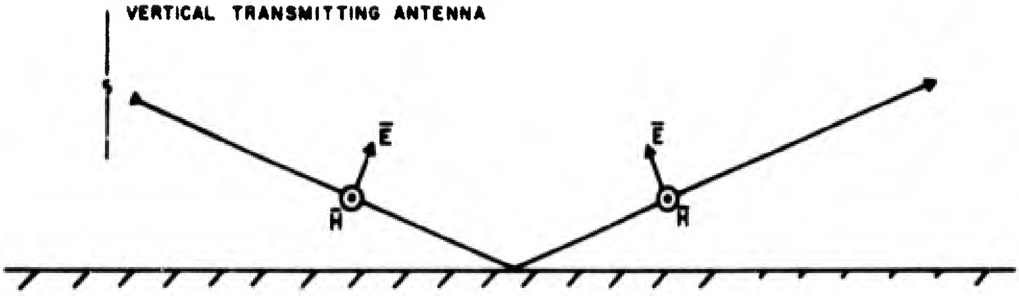

Figure 1. Transverse Magnetic (TM) Waves

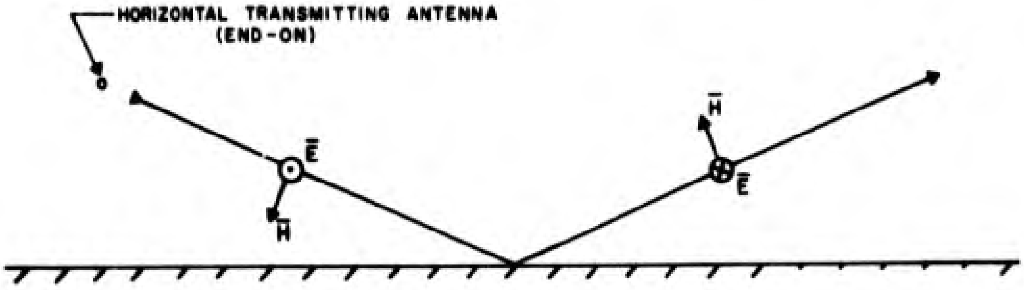

Figure 2. Transverse Electric (TE) Waves

More recently, Reder and Westerland[3] pointed out that TE waves should propagate with surprisingly little loss even over deep Arctic ice which attenuates conventional TM waves. However, except for some low altitude aircraft data reported by Gallenberger and Bickel[4] very little has been published on full-scale observations of man-made TE waves. The development of the balloon instrumentation, and the field experiment, described in this report took place in the period 1969 to 1971.

2. QUALITATIVE CONCEPTS

To the extent that the earth and the ionosphere may be considered to be a flat waveguide for low frequency waves, the distribution of field intensity with altitude

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[3] Reder, F.H., and Westerland, S. (1973) J. Atmos. Terr. Phys. 35:1475-1491.

[4] Gallenberger, R.J., and Bickel, J.E. (1971) Horizontal and Vertical Atmospheric Noise Measurements at VLF up to 20,000 ft Altitude, Naval Electronics Laboratory Center Technical Report 1793.

may be thought of as resulting from the interference of elementary up-going and down-going plane waves reflecting from the boundaries at certain oblique (modal) angles of incidence. At these angles the phase changes due to reflection are such that the up-going and down-going waves are consistent with each other. With TM-polarized waves the phase-change on reflection depends quite critically on whether or not the angle of incidence is above or below the quasi-Brewster angle. Table 1 gives approximate Brewster angles calculated for 45 kHz plane waves and selected examples of reflecting surface.

Table 1. Quasi-Brewster Angles for 45 kHz TM Waves

Type of Surface Description	σ	ϵ/ϵ_0	Brewster Angle (Approximate)
Sea Water	4	80	89^o
Good Soil	10^{-2}	20	88^o
Fresh Water	10^{-3}	80	87^o
Poor Soil	10^{-3}	10	87^o
Thick Ice	2×10^{-5}	5	71^o
Ionosphere $\beta = 0.5$ $h = 70$			65^o

For most common types of earth, 45 kHz TM waves incident at angles less about 87^o (below the Brewster angle) may be regarded as reflecting with no large change of phase. On the other hand, the same waves incident on a flat ionosphere at angles greater than about 65^o are beyond the Brewster angle, and may be thought of as reflecting with a nearly 180^o phase change.[5] Thus, for incidence-angles between 65^o and 87^o, the modal structures for TM waves between a flat earth and a flat ionosphere tend to be roughly of the forms shown in Figure 3(a). Rocket probes instrumented for TM-wave reception have actually shown amplitude-height profiles strongly resembling those of Figure 3(a).[6] For the efficient coupling to such modes, an electric dipole transmitting antenna should be vertical, and preferably close to the ground surface.

Most common surfaces are sufficiently well-conducting at low frequencies to give a phase change of nearly 180^o on reflection for TE waves at all angles of incidence. There is thus a field-cancellation effect at the ground, and the modal

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[5] Kossey, P.A., Rasmussen, J.E., and Lewis, E.A. (1974) Lower Ionosphere Structure, Akademic-Verlag, Berlin.

[6] Harvey, R.B., Harrison, R.P., Fields, V.C., Hirst, G.C., Kossey, P.A., and Lewis, E.A. (1973) AFCRL Report No. 73-0293.

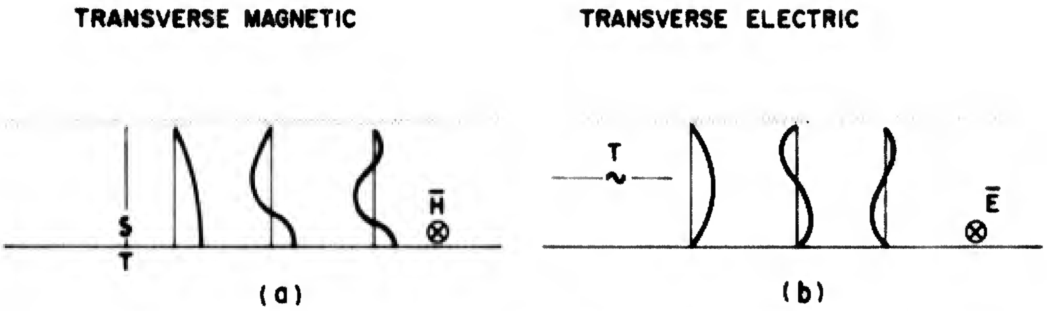

Figure 3. Types of Propagating Modes

structures for TE waves should resemble those illustrated in Figure 3(b), which show little or no transverse electric field at low altitudes. (There is a slight longitudinal magnetic field, but this vanishes as the angle of incidence becomes grazing.) Accordingly the observation of TE waves ideally requires receiver probes at altitudes amounting to an appreciable fraction of the distance between the ground and the ionosphere — a dimension in the order of 70 km in the daytime, and perhaps 80 km at night. Similarly, for efficient excitation of the TE polarization, the transmitting antenna should also be at a high altitude, and in the horizontal orientation. Since ARC-96 airborne trailing wire antennas are perhaps 90 percent horizontal, and only 10 percent vertical, there is a possibility that a considerable fraction of the transmitted power appears in the TE polarization. The TE fields should be radiated predominantly in the broadside directions, whereas the TM fields from the vertical component of the antenna should be more nearly independent of azimuth.

It should be mentioned that propagating modes in the TE and TM polarizations are not strictly independent because of cross-coupling in the ionosphere due to the geomagnetic field. The well-known "night effect," which causes errors in certain low-frequency direction finders, is due to the partial conversion of TM waves into TE waves. However, under normal daytime conditions, and more especially under heavily disturbed ionospheric conditions, the waves tend to be reflected at lower altitudes where electron collision reduces the role of the earth's magnetic field. In these cases, it is appropriate to think of the two polarizations as existing simultaneously, and independently.

Table 2 summarizes the wave-field components to be expected at high altitudes broadside to a high-altitude trailing-wire transmitting antenna, as deduced from simple qualitative arguments. Evidently an experimental TE/TM comparison could be made by observing either the electric, or the magnetic, wave components.

Table 2. Qualitative Summary of Field Components

		Field Components		
			Horizontal	
Field	Wave Type	Vertical	Transverse	Longitudinal
Electric	TM	Strong	0	Weak
	TE	0	Very Strong	0
Magnetic	TM	0	Strong	0
	TE	Very Strong	0	Weak

3. INSTRUMENTATION DESIGN

The balloon-probe experiment (Figure 4) was designed to sense the vertical magnetic field of the TE wave from an ARC-96 transmitter at operational altitudes. The decision to sense the vertical magnetic, rather than the horizontal electric field (Table 2) was based on considerations of practical convenience. (Loop antennas operate at a lower effective impedance level, and are believed to be less sensitive to precipitation and atmospheric-electric noise, than short electric dipole antennas.) For simplicity the payload had a single, nominally horizontal, loop antenna hexagonal in form, consisting of 30 turns of litz wire supported by three light wooden bars about 1.5 m long, shown in Figure 5. The antenna hung by a bridle of nylon cord attached to a small safety parachute which in turn hung from the balloon as illustrated in Figure 4. The balloon was a standard 1200 gm type commonly used for meteorological purposes. The total payload was 2.5 lb (1.1 kg) which allowed an altitude capability in the order of 75,000 ft (23 km), and an initial ascent rate of about 1000 ft per minute.

When observed with binoculars, the loop antenna was seen to swing back and forth with a pronounced pendulum motion, presumably induced by wind shears and by turbulence from the ascending balloon. This pendulum motion made it possible to recognize from the character of the Low Frequency signal strength records, when the TE polarization was much stronger than the TM and vice versa.

Figure 6 illustrates the case of a dominant TM wave (no TE) with its horizontal magnetic field oscillating at wave frequency in the plane of the figure. If the loop swings back and forth in a plane perpendicular to the paper no TM field lines link it, and no signal is picked up. However, this particular motion is very unlikely to occur in practice, and, in general, there will be components of motion in the plane of the diagram. When the loop is in position A there is some field

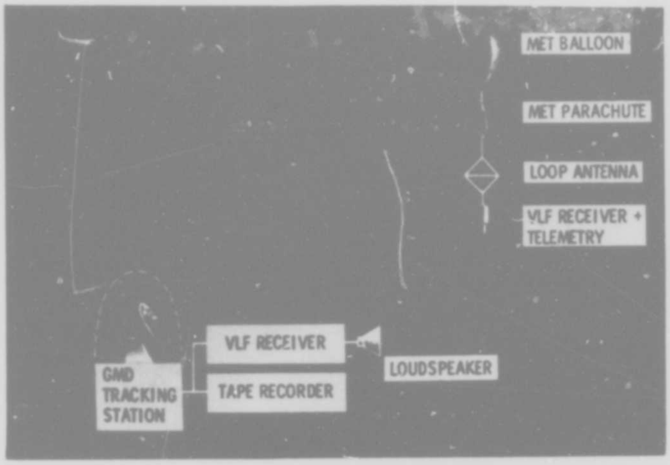

Figure 4. Balloon Probe Concept

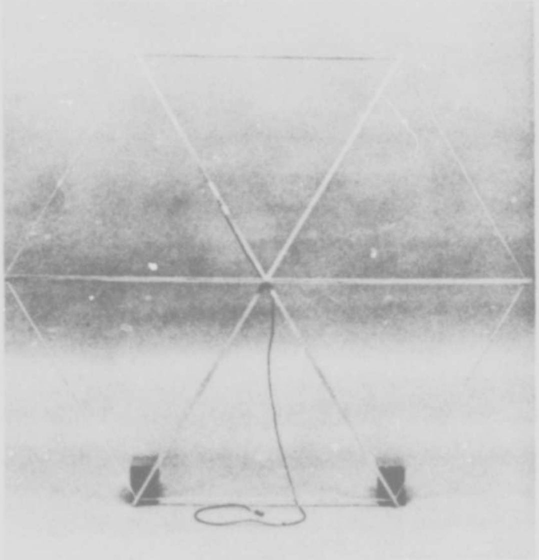

Figure 5. Loop Antenna

linkage and thus some signal pickup. As the loop moves toward 0 the signal decreases to zero, and increases again as position B is approached. The signal amplitude as a function of time would, therefore, give a deeply serrated record, as illustrated. In tests made with a captive payload suspended above the ground, and caused to swing through an arc by pulling on a nylon line, the associated modulations of the signal from a TM-polarized wave were actually demonstrated to be of the type described.

The other extreme case, with only a TE wave present, is shown in Figure 7. Here the magnetic field of the wave is vertical, and unless the loop swings to $\pm 90^{\circ}$, there is always some signal voltage induced. The amplitude-time record is then only slightly undulating as illustrated. Thus, by qualitatively examining the type of record obtained experimentally, a judgment can be made as to whether Figure 6 or Figure 7 is more nearly representative of the data in cases when one wave-polarization is dominant. The instrumentation package, containing the receiver, battery pack, and the telemetry unit, was suspended below the antenna. This package was improvised from a standard 1680 MHz radiosonde, see Figure 8, containing a water-actuated battery pack which generated heat and thus helped maintain a constant temperature during flight.

The receiver, Figure 9 was of printed circuit construction and weighed only 33 gm. The antenna-receiver combination had a wide, flat frequency band-pass (5 to 60 kHz) and frequency-modulated the telemetry transmitter which was laboratory modified specifically for this purpose. The telemetry signal was tracked by standard type GMD meteorological equipment located at Hanscom Air Force Base, Bedford, Mass. As indicated in Figure 4, the LF signal was recovered, and recorded on magnetic tape for subsequent analysis in the laboratory. During flight, signals could be monitored directly with a standard receiver.

The original radio-sonde package contained a barometric switch with 150 contact segments corresponding to known increments of pressure. This device was modified to change the receiver gain, which varied by a fixed 25 dB depending on whether the contact arm was on a segment, or on the space between segments. This arrangement effectively increased the dynamic range of the signal channel, and also made it possible to determine the altitude of the probe at any time on the upward flight by relating the number of observed gain-changes to increments of pressure.

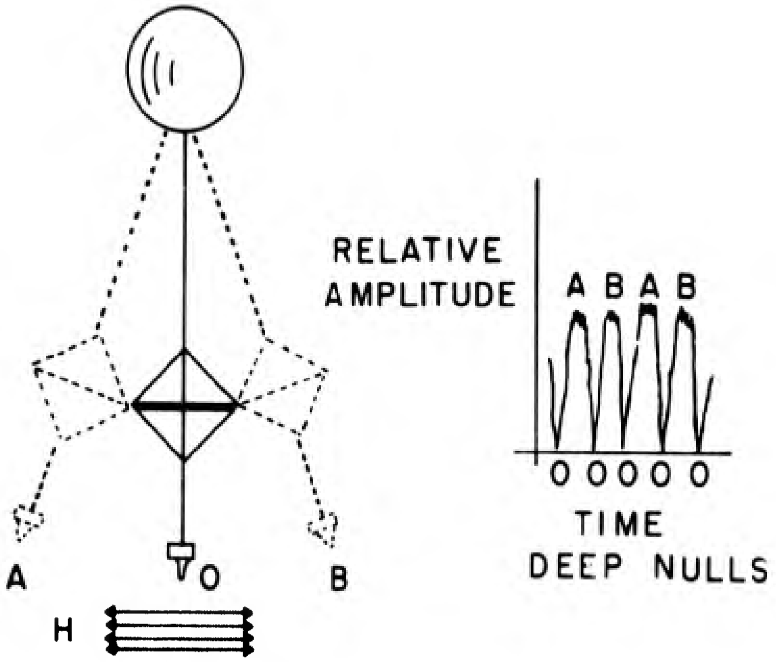

Figure 6. Case I – TM Polarization Dominant

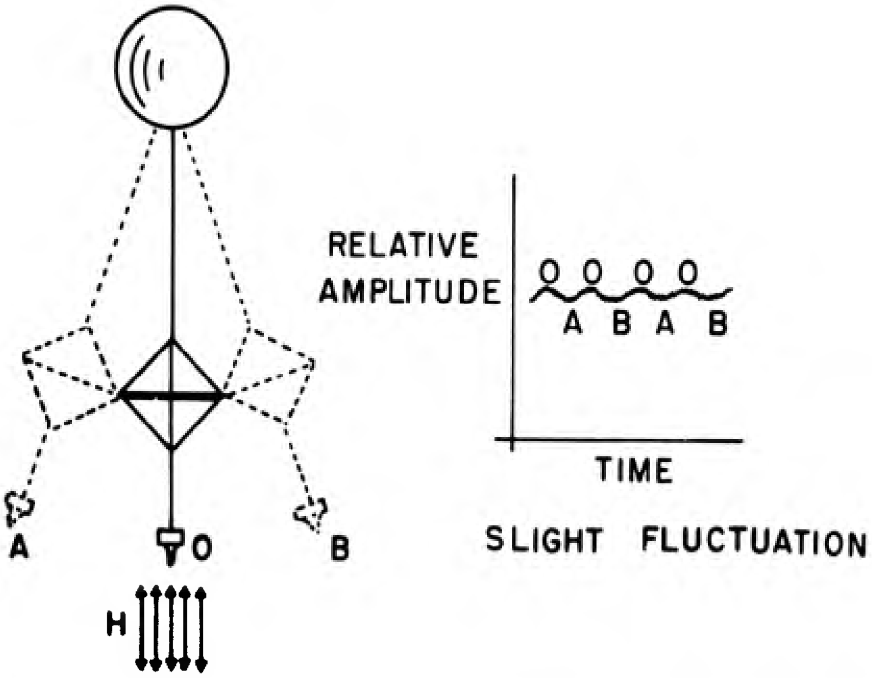

Figure 7. Case II – TE Polarization Dominant

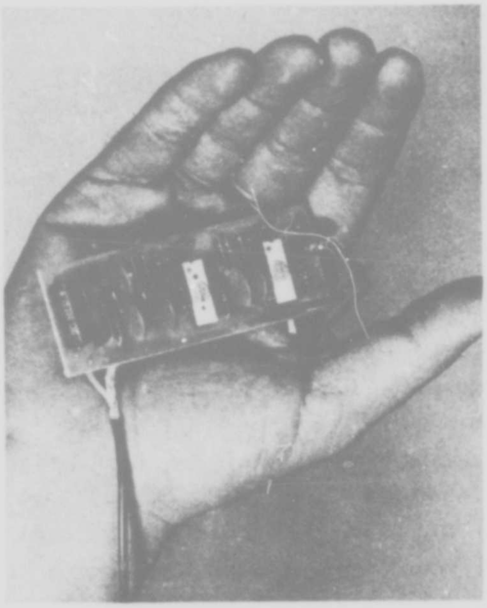

Figure 8. Modified Radiosonde with L.F. Receiver

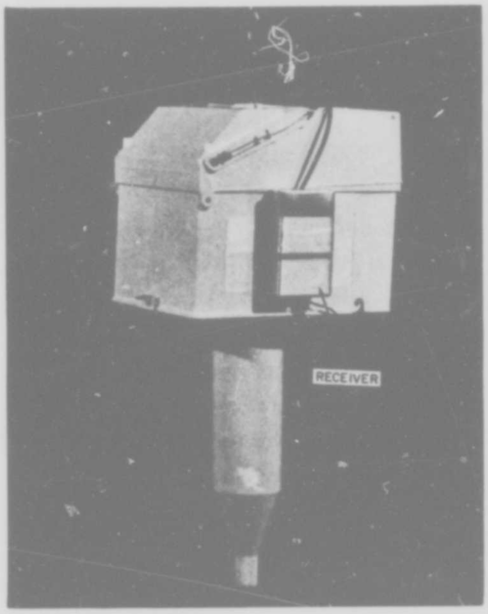

Figure 9. L.F. Receiver

4. EXPERIMENTAL RESULTS

Although several balloon flights were made, this report describes only the probe launched from Hanscom Air Force Base at 1430Z, on 30 March 1971, which provided data of special significance. During a portion of this flight, when the balloon was ascending from about 35, 000 to 44, 000 ft (10. 6 - 13. 4 km),* transmitters on the air included: (a) an Air Force "NEACP" with ARC-96 trailing wire system operating at 44 kHz in an area off Norfolk, VA, (b) a U. S. Navy "TACAMO" aircraft operating at 23. 0 kHz in an unknown location, and (c) several fixed ground stations including NAA at Cutler, ME, operating at 17. 8 kHz.

On play-back of the magnetic tape record of the flight, a low frequency receiver could be tuned to any frequency in the 5 kHz to 60 kHz pass-band of the probe instrumentation. By making chart recordings of the amplitudes of the various signals on the tape, one after another, and then aligning the charts in time register, the relative behavior of the signals could be compared. Figure 10 shows on logarithmic amplitude scales, signal strength versus time records for TACAMO, NAA, and NEACP for one 7-minute portion of the flight record. In interpreting these data, allowance must be made for the gain changes in the balloon probe caused by the operation of the barametric switch as explained in Section 3. Figure 11 is similar to Figure 10 but vertical line have been added to indicate time intervals of high gain labeled H. During the intervals designated by the letter 0 the NAA signal went off the air briefly.

The NAA and TACAMO signals were of the "CW" type, and were keyed at a rate slow enough for the recording pen to respond, giving records with an "inked in" appearance. Nevertheless, it is clear from Figures 10 and 11 that within the high-gain segments, the NAA signal shows the deep serrations expected for a standard TM signal caused by the swinging of the loop antenna as discussed in Section 3. Other ground stations gave similar serrated records.

The NEACP signal was FSK modulated, but the play-back receiver was center-tuned so that the response was the same on both upper and lower frequencies causing the pen of the chart recorder to indicate a thin line with no variations due to the signal modulation. Within the high-gain segments, the NEACP signal in Figures 10 and 11 shows no evidence of the deep serrations so prominent in the NAA record, but is nearly constant as would be the case for a TE-dominant signal as discussed in Section 3. (Note: the NEACP transmission ceased abruptly near the end of the 7-minute time sample.)

TACAMO aircraft commonly fly in circles of small radius so that their antenna wires hang more vertically than ARC-96 antennas trailed from high speed

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*The solar zenith angle was approximately 49. 7°

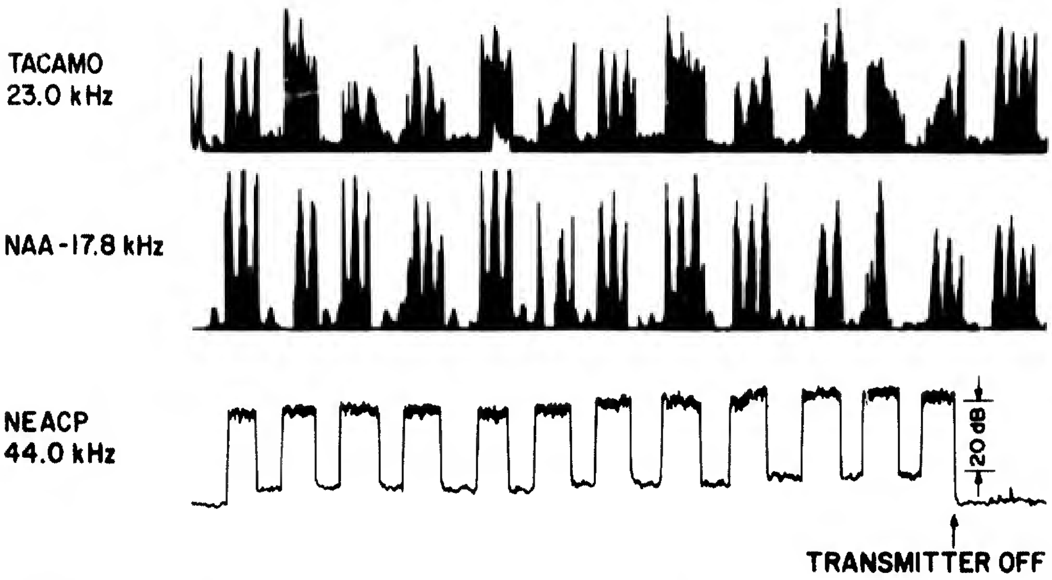

Figure 10. Signal Records From a Seven Minute Segment of Tape Arranged in Time Register.

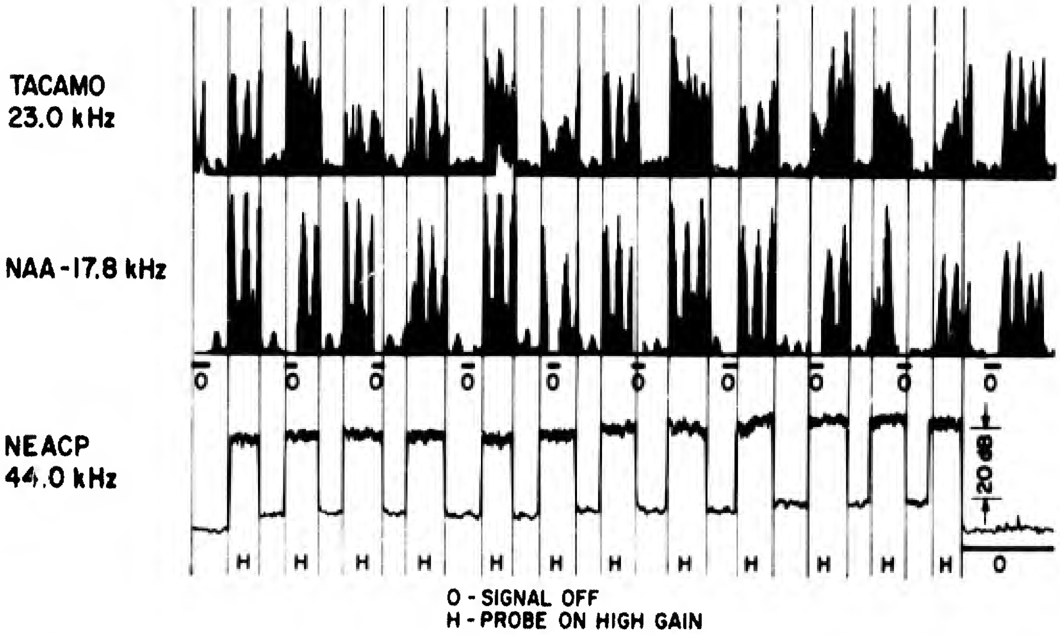

Figure 11. Signal Records Keyed to Show Gain Changes and Transmission Breaks

Air Force aircraft in level flight. The TACAMO signal might, therefore, contain a more equal mix of TE and TM components, and this surmise is consistent with the appearance of the TACAMO record in Figures 10 and 11; the signal minima are not so deep as those of NAA, nor is the signal level so constant as with the NEACP transmitter.

5. CONCLUSIONS

The great constancy of the signal from the NEACP ARC-96 trailing-wire transmitting antenna despite the pendulum motion of the receiving antenna, which caused severe amplitude-modulation of known TM-polarized signals, furnishes strong evidence that the NEACP radiation was predominantly TE-polarized in the case observed. If further research shows this to be a consistent and reliable aspect of trailing-wire transmissions, it could have important implications for high altitude air-to-air communications.

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