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DEMONSTRATION OF TRANSVERSE ELECTRIC (TE) MODE RADIO PROPAGATION IN THE EARTH-IONOSPHERE WAVEGUIDE

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Air Force Cambridge Research Laboratories
L. G. Hanscom Field, Massachusetts

24 January 1974

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13. ABSTRACT

As part of the Air Force Support to the Minimum Essential Emergency Communications Network, (MEECN), AFCRL has been exploring the use of Transverse Electric (TE) Modes of propagation rather than the conventional Transverse Magnetic (TM) Modes at Very Low Frequencies. Theoretical comparisons show that TE waves should propagate better than TM waves in the earth-ionosphere waveguide under both normal and disturbed ionospheric conditions. Electromagnetic boundary conditions at the surface of the earth prevent efficient excitation and reception of radio waves generated in the TE Mode, but at higher altitudes, air-to-air communications is a practical reality. Instrumentation developed at AFCRL provides a means for conducting high altitude measurements, In the present system, a weather balloon carries a payload to 70,000 feet or more and drops it. The free falling payload is dartshaped and stabilized aerodynamically to better than one degree of verticality. Signals from TE and TM polarizations are received individually and transmitted to the ground. Instrumentation used in measurements will be discussed and data will be presented showing results of measurements of Very Low Frequency TE and TM signals, and of VLF background noise which comes primarily from lightning strokes propagating in the TE and TM modes over great distances. The experiments were conducted at Swan Island, West Indies, Churchill Research Range, Canada and Canton Island in the Pacific.

Biographical Sketch

Robert P. Harrison was born in Boston, Mass. on July 25, 1919. Following service with the Navy in World War II, he worked with the Naval Research Laboratory, Naval Air Development Center, M.I.T. Lincoln Laboratory on data transmission, reception and processing techniques. Since 1960 he has been with the Electromagnetic Environment Branch of the Ionospheric Physics Laboratory, AFCRL, Bedford, Mass., performing ground-based and rocket and balloon-borne electromagnetic experiments.

For communications that will survive the ionospheric disturbances caused by nuclear explosions and natural phenomena such as Polar Cap Absorption events (PCA's), the Air Force is developing systems using Low Frequencies (LF) and Very Low Frequencies (VLF) because these waves propagate better than most frequencies under disturbed ionospheres.

Long Range propagation of radio waves Figure 1 takes place by what amounts to a series of reflections in a wave-guide formed by the earth and the ionosphere. Some energy is lost on each reflection, particularly in Arctic regions and when the ionosphere has been disturbed. To minimize these losses and obtain better propagation efficiency, AFCRL has been investigating the use of the Transverse Electric (TE) polarization instead of the Transverse Magnetic (TM) polarization conventionally used in LF/VLF communications systems.

The TM waves shown on the left in Figure 2 are radiated from vertical ground based antennas. These waves are strongest near the surface of the earth but become weaker with altitude. TE waves are radiated from horizontal antennas and these waves are strongest at high altitudes, but much weaker near the ground.

Very little work has been done with TE waves, even though calculations show that these waves propagate with less attenuation, especially in Arctic regions where it was found that over Greenland ice, the reflectivity of TE waves is 700 percent better than TM waves, and for a normal daytime ionosphere, it is forty percent better. Under severely disturbed ionosphere conditions, the reflectivity can be twice as good for TE.

Background noise at LF and VLF comes primarily from lightning strokes occurring nearby and from distances of many thousands of miles. Since lightning may be a discharge between a cloud and the ground (TM) or from a cloud to another cloud (TE), then the total noise levels of each, if compared, might not necessarily be the same.

Electromagnetic boundary conditions on the ground make TE waves difficult to excite and difficult to receive unless both terminals are airborne. However, the Air Force has experimental aircraft equipped with ARC-96 transmitters using extremely long trailing wire antennas. Even though these horizontal antennas droop down about ten percent, theoretical investigations at AFCRL indicate that this type of antenna should excite TE modes in a more efficient manner.

Since TE waves are weak at ground level and are expected to be stronger above the ground, we needed an airborne receiving platform which would be capable of reaching very high altitudes. Aircraft were considered, but a few simple tests around the fuselage of a KC-135 were enough to indicate that VLF waves are so severely distorted, there was considerable doubt that meaningful measurements could ever be made. Also, operating an aircraft is quite expensive and although rockets would be suitable for airborne measurements, they too are very costly.

The technique we conceived and developed is illustrated in Figure 3. In this system, a weather balloon carries a specially instrumented package to 100,000 feet. On the ground, a GMD tracking receiver, ordinarily used for tracking standard balloon-borne weather radiosondes, follows the special instrument in flight.

The balloon package has a large five foot diameter loop antenna, mounted horizontal to the ground for the reception of TE signals. The loop is connected to a wide band LF/VLF receiver which modulates the modified radiosonde transmitter. The LF/VLF receiver, was designed and built at AFCRL and weighs only a few ounces. The receiver package is taped to the side of the radiosonde box, Figure 4, The radiosonde box contains a battery, an aneroid barometer and the radiosonde transmitter. The entire package, including the loop antenna weighs only a few pounds and is easily carried aloft by a standard 1200 gram weather balloon. Several of these packages were flown at AFCRL to altitudes of 100,000 feet or more.

This particular configuration was not without problems, however, especially with the stability of the loop antenna, which tended to swing continuously like a pendulum below the balloon. However, this problem can be turned into an advantage.

Figure 5 illustrates the swinging loop picking up a signal from a ground based VLF transmitter. Ground transmitters use vertical antennas which radiate in the TM mode. TM waves have a magnetic field horizontal to the earth. If the loop antenna in the illustration is horizontal, no voltage should be induced by the magnetic field. However, if the loop swings to the right or to the left, it will begin to pick up this magnetic field.

In Figure 6, the magnetic field is from a TE wave. This field is vertical and thereby induces a large voltage in the loop. If the loop should swing to the right or to the left, the change in induced voltage will be very slight.

In the spring of 1971 during one of our balloon flights at AFCRL, we monitored transmissions from two trailing wire aircraft. One of these planes equipped with an ARC-96 was trailing a long horizontal wire, and the second aircraft was flying in a circular orbit which forced the trailing wire into a vertical spiral. Signals from these aircraft along with signals from other ground based stations were picked up by the swinging loop and were telemetered through the radiosonde transmitter to the GMD tracking system on the ground. In Figure 7, the display of NAA illustrates how a TM wave should behave. As the loop swings, the amplitude of the signal rises and falls, occasionally going into a low amplitude or null. The signal from the horizontal wire radiating a TE wave is shown at the top. Here, as the loop swings back and forth, the amplitude of the TE wave remains reasonably constant, except for the slow increase in amplitude over a period of several minutes. The signal from the spiralling antenna seems to be a combination of the other two. The nulls are not quite as deep, and the amplitude varies less than the NAA signal, suggesting the wave from it is a mixture of TE and TM. Data in this illustration represents the first evidence ever presented that radiations from a horizontal trailing wire antenna are predominantly TE. During this seven minutes, the balloon package was rising from about 38,000 to 45,000 feet. The illustration suggests that the amplitude of a TE wave also rises with altitude.

At this point, it was evident that much more TE data was needed to show the advantages of using TE mode for air-to-air communications. Vertical profiles showing TE amplitude variations across the earth-ionosphere waveguide were needed for the altitudes normally used by military aircraft in flight. Both TE and TM wave transmissions from trailing wire aircraft should be measured and compared either simultaneously or sequentially. Our airborne platform should therefore be stable enough to insure that comparisons of TE and TM would be more meaningful. A stable platform would also enable us to compare TE and TM background noise.

Figure 8 is a sketch of the package we conceived. The package is shaped like a dart, is made from a cardboard mailing tube having metal fins mounted on one end and a plastic ogive at the other. The tube is 5 inches in diameter and has a total length of 43 inches. Two loop antennas are mounted in the package, one oriented for TE wave reception and the other oriented for TM. A switching circuit alternately switches the TE and the TM loops to the input of the VLF receiver which modulates the radiosonde transmitter. The entire package weighs only three and one half pounds and is carried aloft with a balloon as before, followed in the usual way by the GMD tracking receiver. When the package reaches 70,000 feet a pressure switch closes and fires a squib. This releases the balloon and allows the dart package to fall free toward the earth. Within seconds after the drop begins, the dart is stabilized to better than one degree of verticality. The GMD tracks the falling dart for the three minutes of droptime. At impact the package is destroyed and is not recoverable.

Figure 9 illustrates the dart instrumentation which consists two loop antennas switched alternately to the VLF receiver and the radiosonde transmitter. The switching period is about one second, as the switcher alternately connects the antennas to the input of the VLF receiver. Since we are comparing the difference between the loop voltages, even if the receiver gain should shift slightly, the relationship of the two loop voltages is not affected. The entire wideband VLF composite is telemetered to the GMD.

At the ground station, Figure 10, a 30 Megahertz FM receiver is connected to the output of the RF mixer of the GMD. This connection has no effect on the operation of the GMD which tracks the dart package in azimuth and elevation for the entire flight. The output of the FM receiver contains the same information as the original VLF composite of the airborne package. This 'original' RF is recorded on magnetic tape and is also passed into a tuneable narrow band filter so that signals of discrete frequencies can be observed. After the flight is over, the tape recorder can be operated in the reproduce mode for additional information.

Before each dart package is launched, both loops are calibrated in a magnetic field, Figure 11. With the dart package operating, a known current is passed through a loop of wire. By knowing the current in the wire and the diameter of the single turn, we can calculate the magnetic field inducing a voltage into the loop antenna of the dart package. This information is telemetered to the FM receiver and recorded on magnetic tape. The TE loop is calibrated with the loop horizontal to the ground (package vertical) as shown in the illustration, and the TM loop antenna is calibrated with the dart package lying on its side. Our present calibration source consists of ten oscillator signals mixed together to form a VLF composite. The frequencies of these oscillators have been adjusted with 5 KHz separation in the LF/VLF spectrum between 15 and 60 KHz. All the oscillator amplitudes are adjusted to equal amplitudes. Two minutes of continuous signals from this calibrator are allowed for the calibration of each loop. After the calibration procedure has been completed, the package is made ready for flight by simply attaching a balloon.

After early tests at Wallops Island in July of 1971, we have dropped our darts at Swan Island, West Indies, the Churchill Research Range, Canada, and Canton Island in the Pacific.

There are no radar facilities at most of these remote sites, except for Churchill, where rockets and balloons are launched daily. However, it was necessary to know the altitude of the dart packages while they were dropping. The AFCRL computer furnished data from which we could construct some altitude - time curves. Figure 12 compares a radar plot of one of our falling darts with the curve drawn from the computer data. The match is very good.

In August of 1972 while at Churchill, we monitored signals from an aircraft operating over Lake Superior. The aircraft was in a racetrack orbit, see Figure 13, flying north and south on 60 mile legs and turning at each end on a ten mile radius. Churchill is located 800 statute miles north of Lake Superior.

With the trailing wire aircraft radiating a signal of constant power, we calibrated and launched a dart package and tracked it in the usual way. The trailing wire signal was monitored continuously through the telemetry link as the dart package ascended to 70,000 feet. At ground level the ground conductivity was poor and the signal was weak, but readable. In Figure 14, the dotted curve shows the field strength of the signal increasing with altitude. It will be noted from this curve, when the package reached 70,000 feet, the trailing wire TE signal was considerably stronger than it was near the ground. During the drop and with the loop antennas still switching, Figure 15, the TE wave amplitude was very much stronger than the TM wave amplitude, again indicating that radiation from the horizontal wire is predominantly TE mode. It can also be observed in the figure how constant the TE signal was, indicating how well the TE loop remained in its horizontal position due to the aerodynamic stability of the falling dart.

Figure 16 illustrates the TE signal amplitude measured during the dart drop, strong at high altitudes and weaker near the ground.

Returning to Figure 14, the TM component of the trailing wire signal is shown as a solid line on the left. It is quite a bit weaker and behaves as expected, strongest near the ground and weaker at higher altitudes.

The antenna wire on the aircraft is essentially an end fed half wave dipole. Because of the very low frequencies used, the total length of this resonant antenna is several thousand feet. A 30 KHz antenna, for example, would be about 16,000 feet long. The radiation pattern of this antenna should be similar to that of a half wave dipole, with maximum signal radiated broadside to the wire and minimum signal radiated off the ends of the wire. Figure 17 compares the theoretical figure eight pattern of a half wave dipole with some data points taken from measurements during the flight of the balloon-borne dart package. The package was ascending from about 60,000 to 65,000 feet while the trailing wire aircraft was turning at one end of the racetrack orbit. The experimental data and the theoretical points are in very close agreement.

This effort at Churchill also provided us with our first comparison of TE and TM background noise. LF/VLF noise comes primarily from lightning strokes discharging from cloud-to-ground (TM Wave) and from cloud-to-cloud (TE Wave). In Figure 18 a measurement of TE and TM noise at 42 KHz shows TM noise to be stronger than TE.

Summarizing the results of these measurements with noise and with the trailing wire aircraft Figure 19, the TE wave radiated from the horizontal antenna was 14 db stronger than the TM wave radiated from the same wire at 30,000 feet. When the lower level TE noise is included, the signal to noise improvement TE to TM is 20 db at 30,000 feet. At 70,000 feet, the TE wave radiated from the horizontal antenna has increased to 19 db improvement over TM, and the TE/TM signal to noise improvement has risen to 25 db.

At Canton Island, we monitored trailing wire aircraft signals coming from ranges of 1000 miles, 1500 miles and 2000 miles. Although the TE signals from the trailing wire were noticeably weaker than at Churchill due to the greater distances involved, TE waves from the horizontal wires were observed by our dart packages on Canton from all of these ranges, while the TM waves from the same antennas were too weak to be observed except for only a few isolated cases.

It has been shown from these tests that air-to-air communications can be improved at LF and VLF by using the propagating TE wave rather than the TM wave radiated from a horizontal trailing wire antenna. In cases of poor ground conductivity, such as at Churchill, it is also possible to receive a TE signal on the ground.

So far, much has been learned, but many more TE and TM wave measurements are needed at high altitudes and on the ground. More tests should be made with trailing wire aircraft flying at different altitudes, different distances, over various kinds of terrains, in the daytime and at night, and during periods of severely disturbed ionospheres.

LIST OF ILLUSTRATIONS

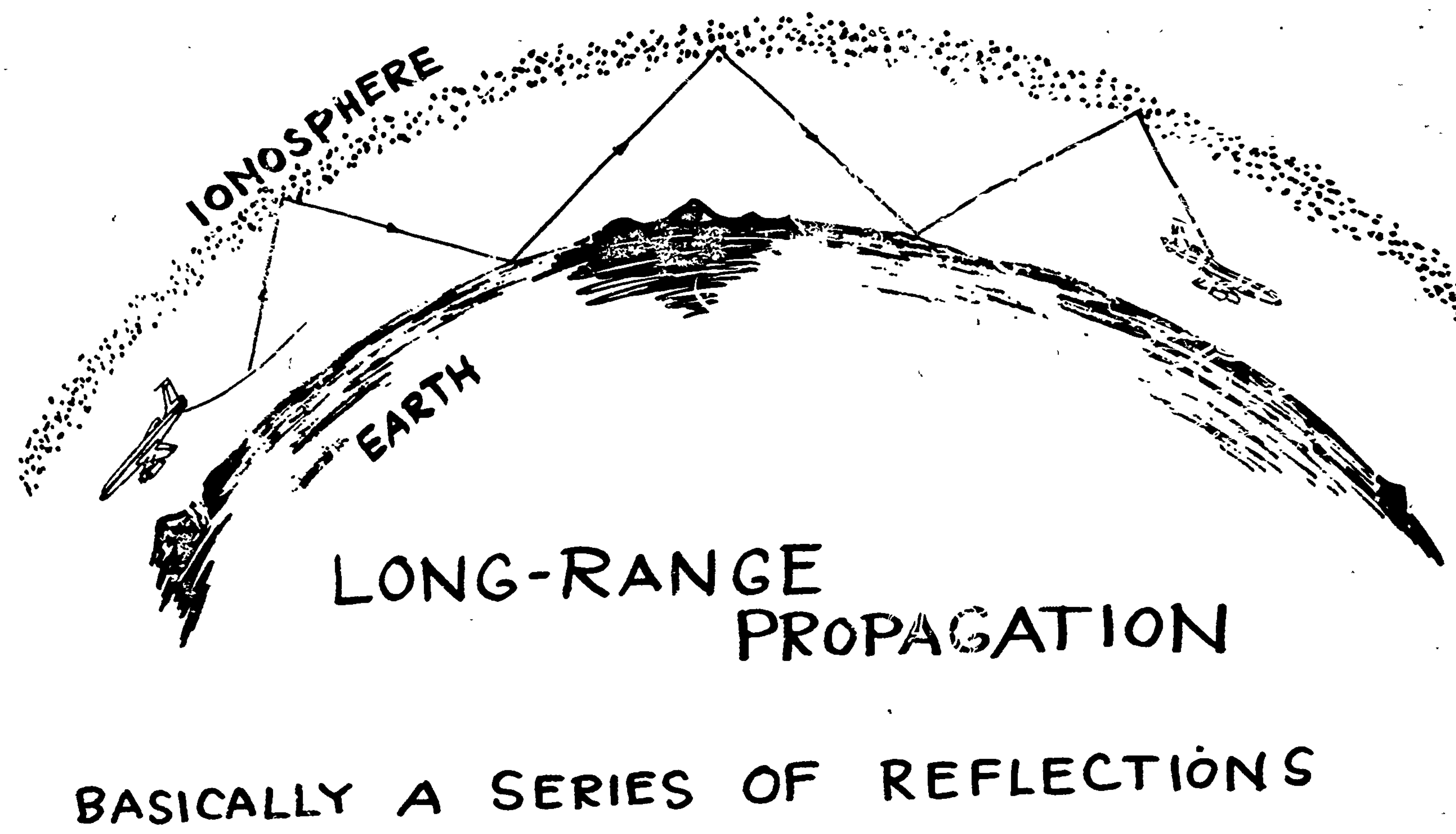
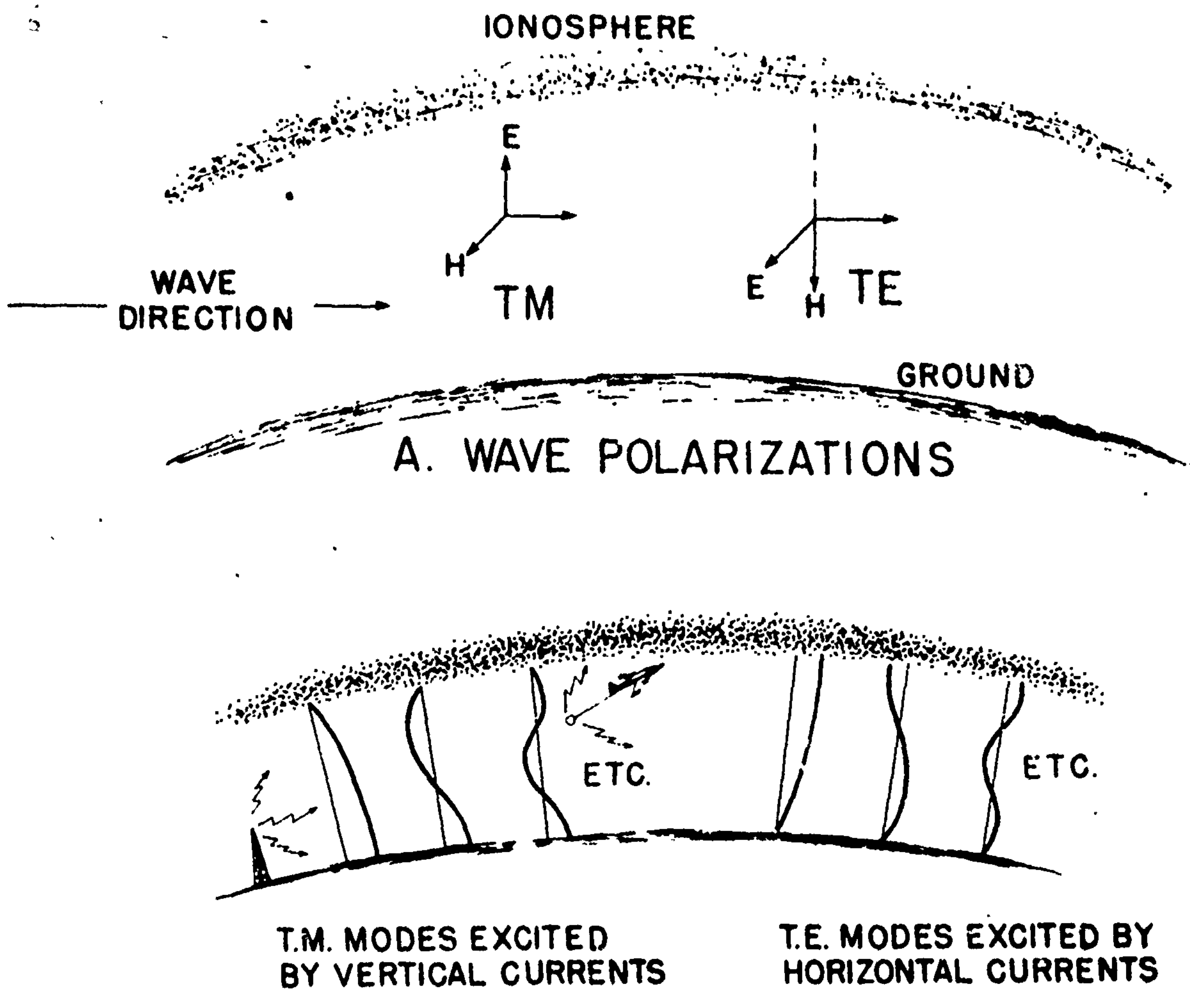

IONOSPHERE
EARTH
LONG-RANGE
PROPAGATION
BASICALLY A SERIES OF REFLECTIONS

FIGURE 1.

CHARACTERISTICS OF TM AND TE MODES

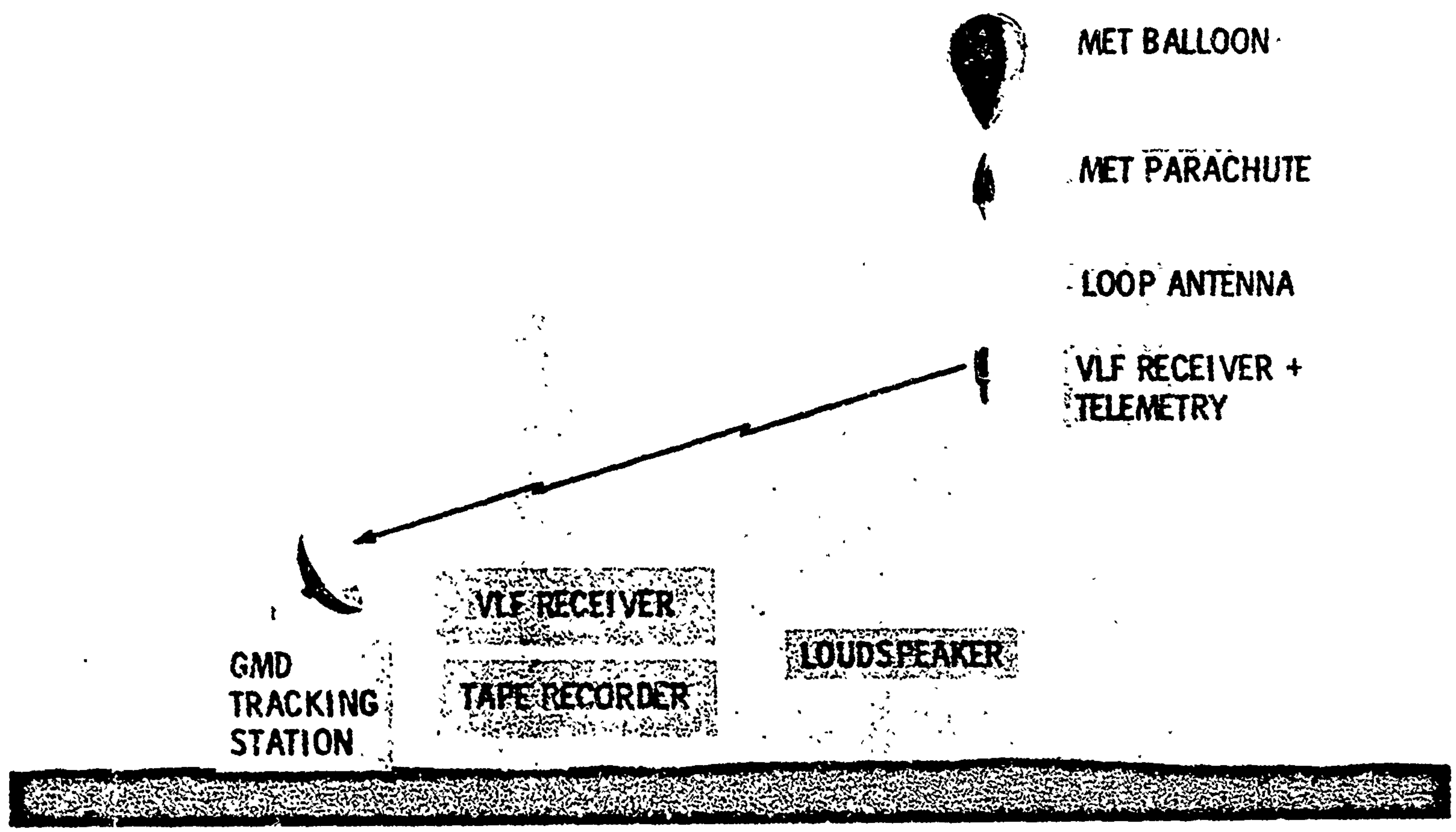


A. WAVE POLARIZATIONS

B. FAMILES OF PROPAGATION MODES

FIGURE 2.

ORIGINAL BALLOON-PROBE CONCEPT



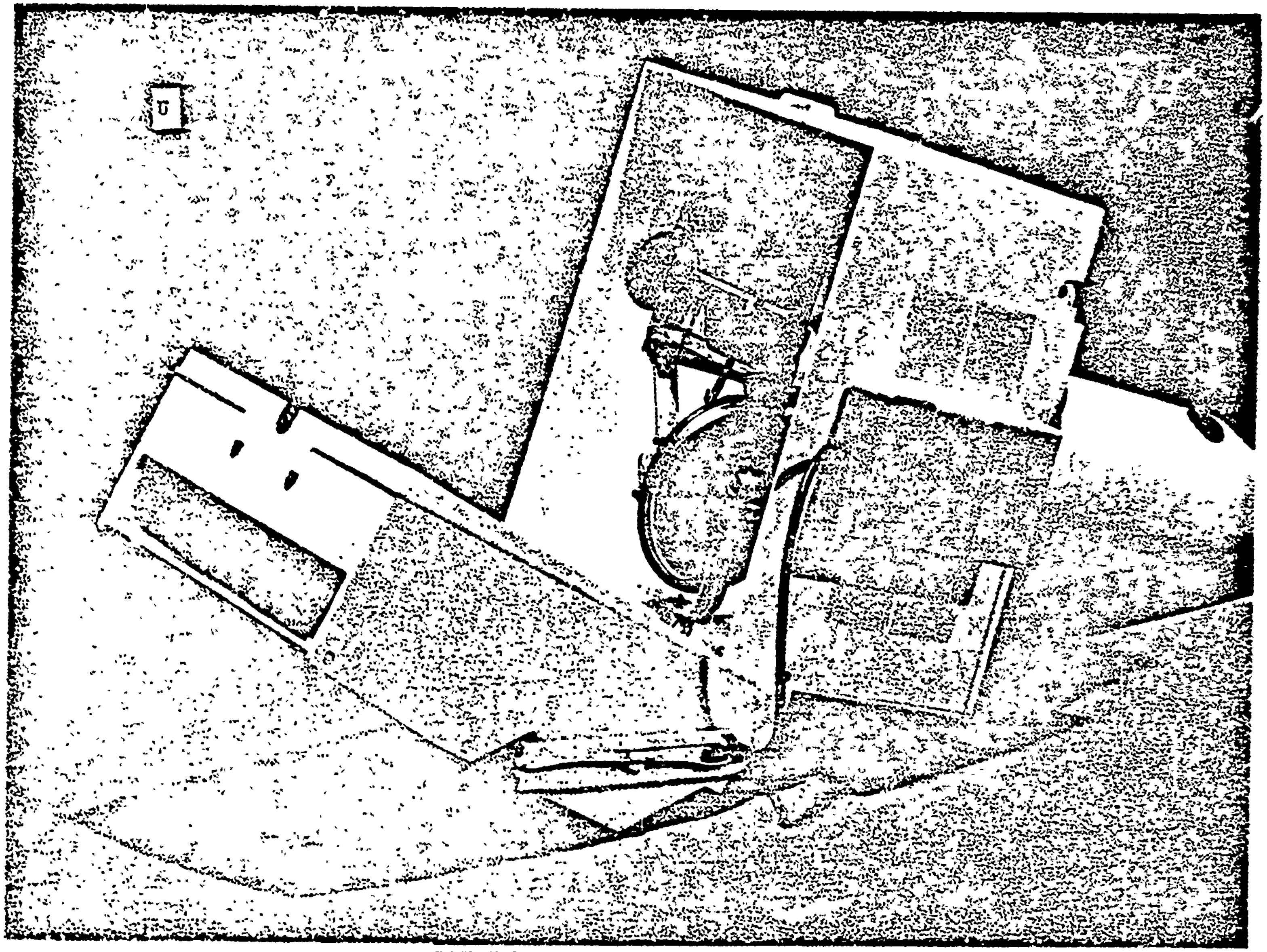


FIGURE 4. MODIFIED RADIOSONDE

CASE I : TM POLARIZATION DOMINANT

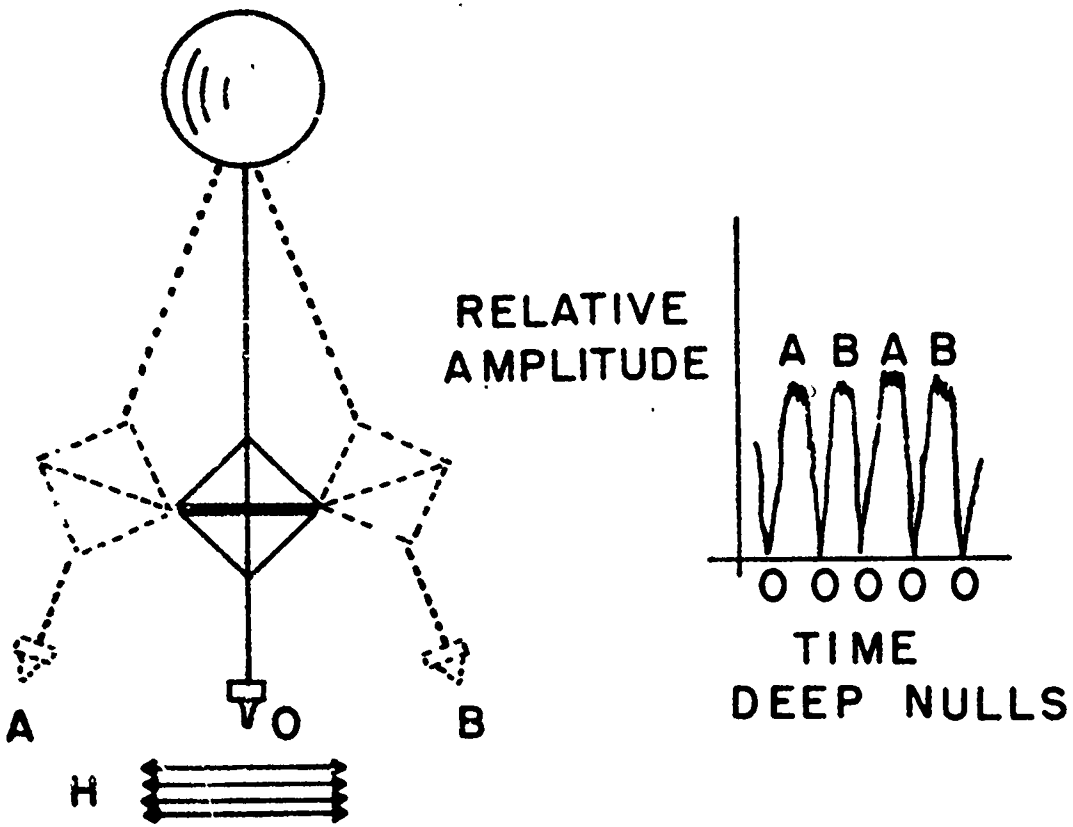


FIGURE 5.

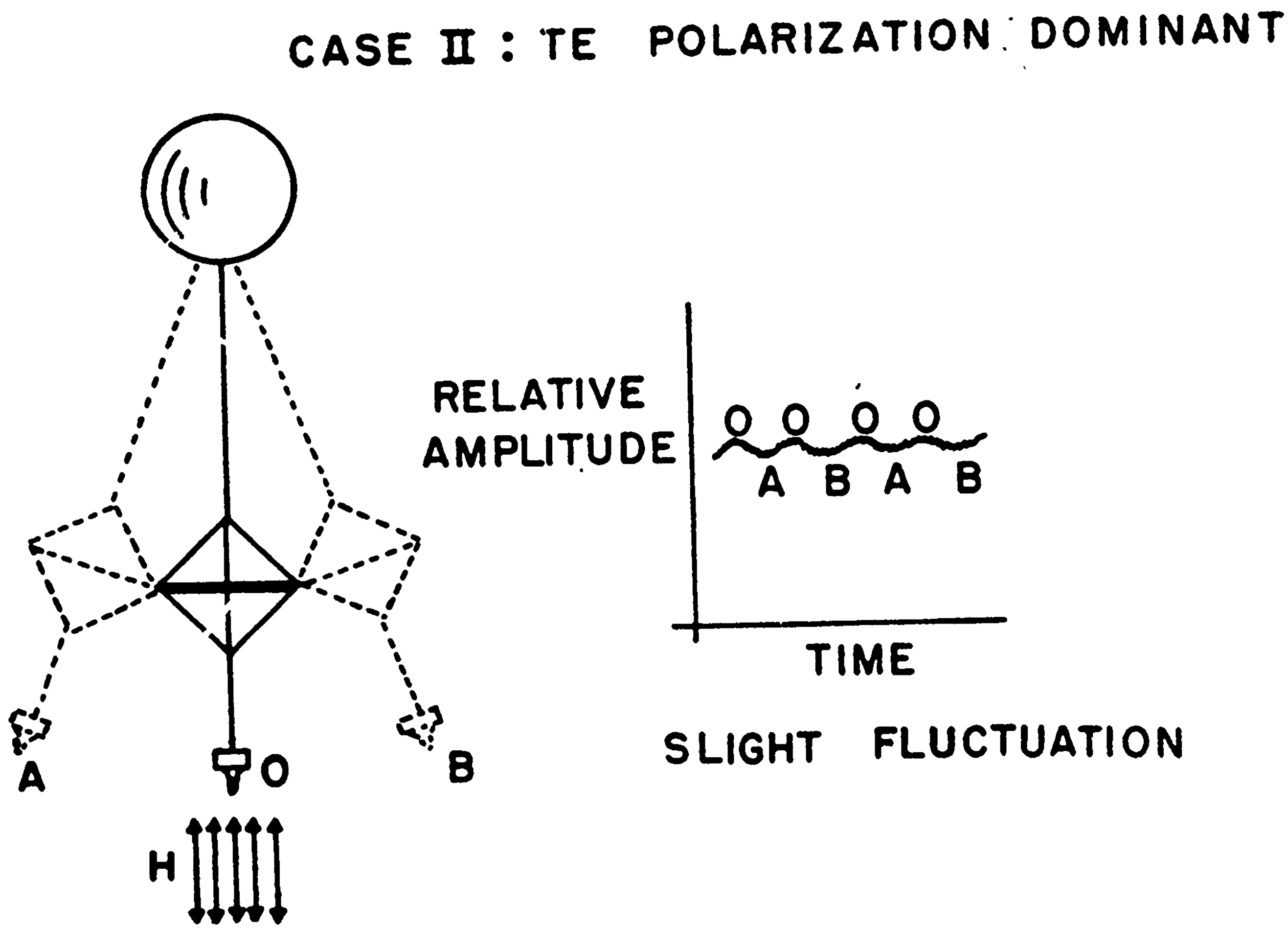

CASE II : TE POLARIZATION DOMINANT
A
O
B
H
RELATIVE AMPLITUDE
O O O O
A B A B
TIME
SLIGHT FLUCTUATION

FIGURE 6.

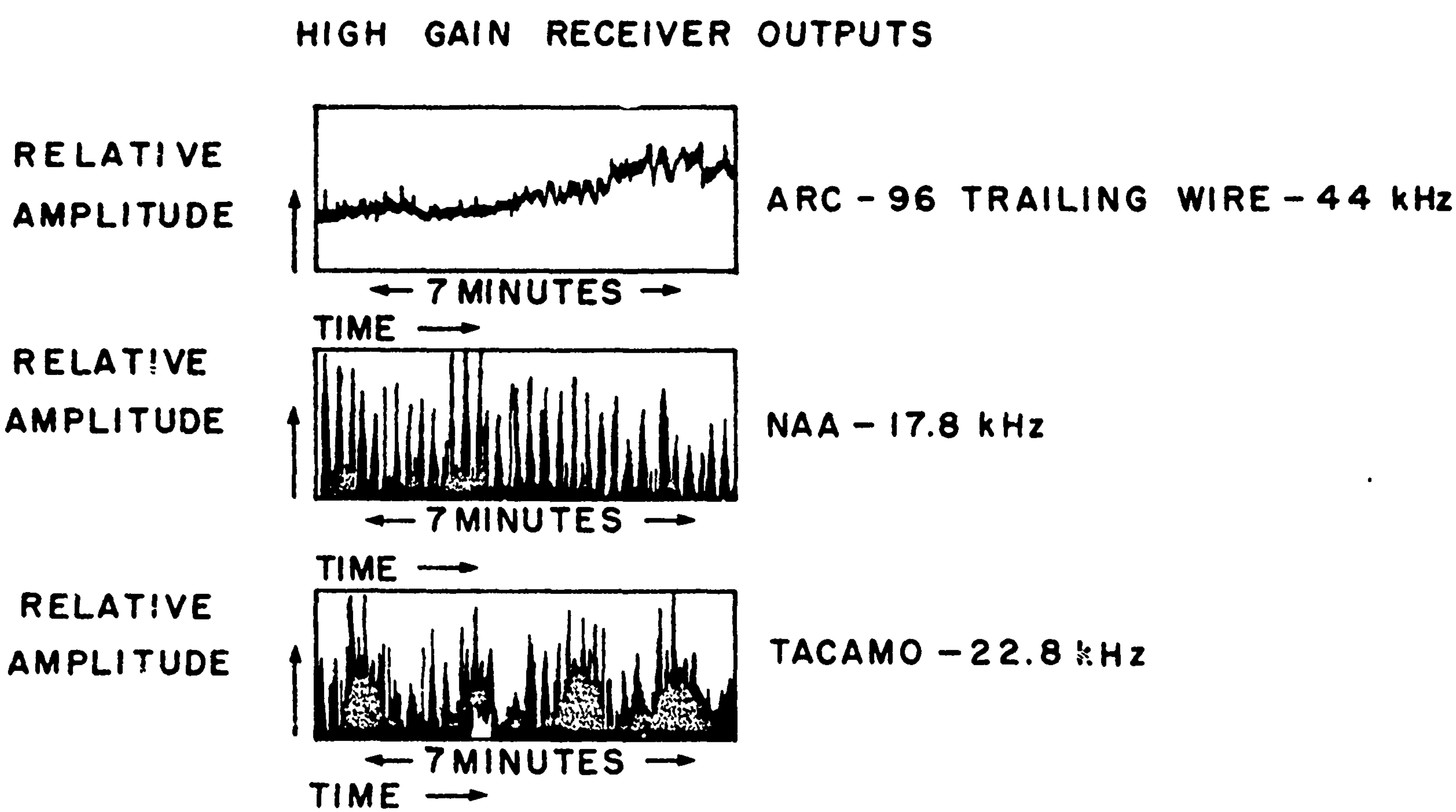

HIGH GAIN RECEIVER OUTPUTS
RELATIVE AMPLITUDE
7 MINUTES
TIME
ARC - 96 TRAILING WIRE - 44 kHz
RELATIVE AMPLITUDE
7 MINUTES
TIME
NAA - 17.8 kHz
RELATIVE AMPLITUDE
7 MINUTES
TIME
TACAMO - 22.8 kHz

FIGURE 7.

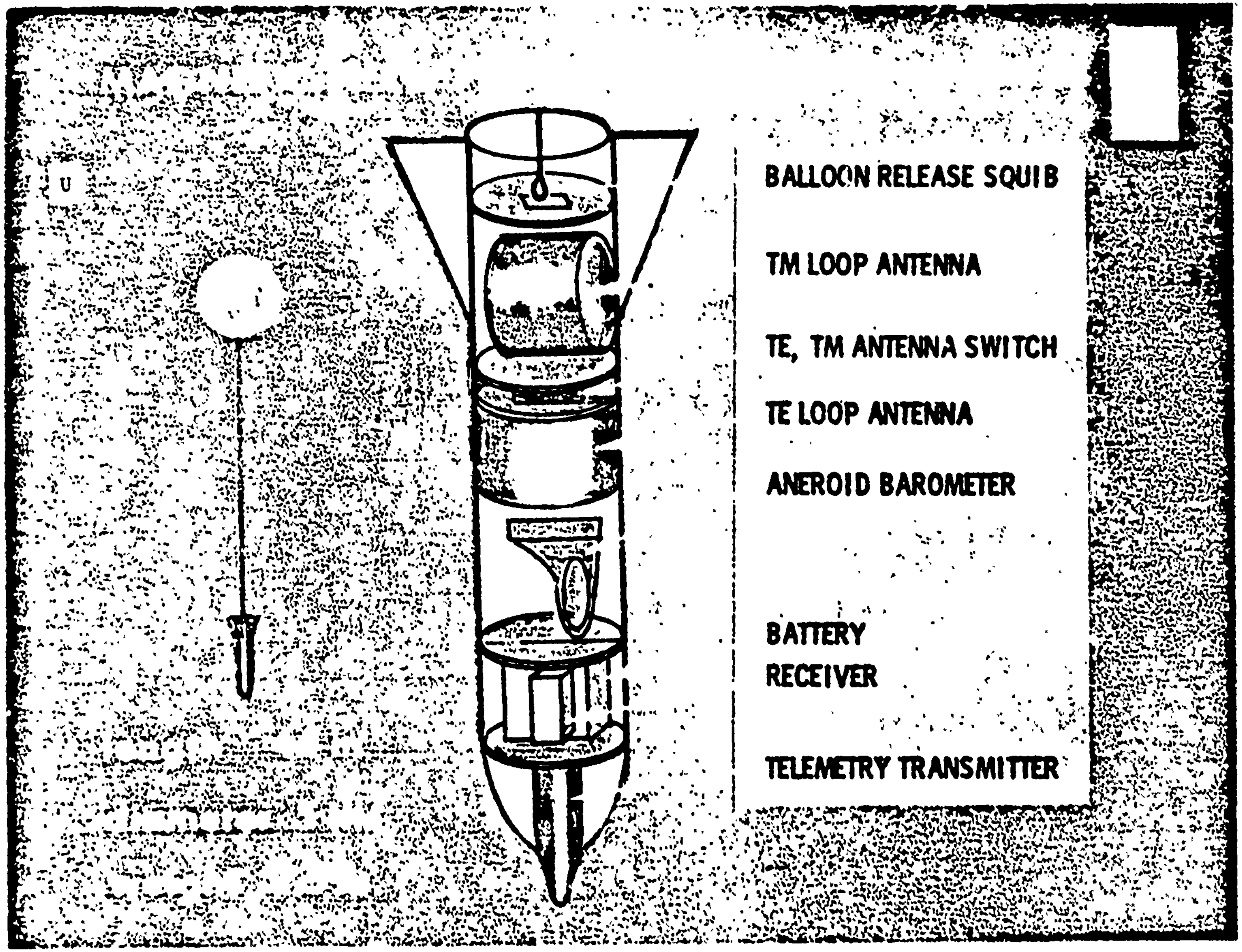

U
BALLOON RELEASE SQUIB
TM LOOP ANTENNA
TE, TM ANTENNA SWITCH
TE LOOP ANTENNA
ANEROID BAROMETER
BATTERY
RECEIVER
TELEMETRY TRANSMITTER

FIGURE 8.

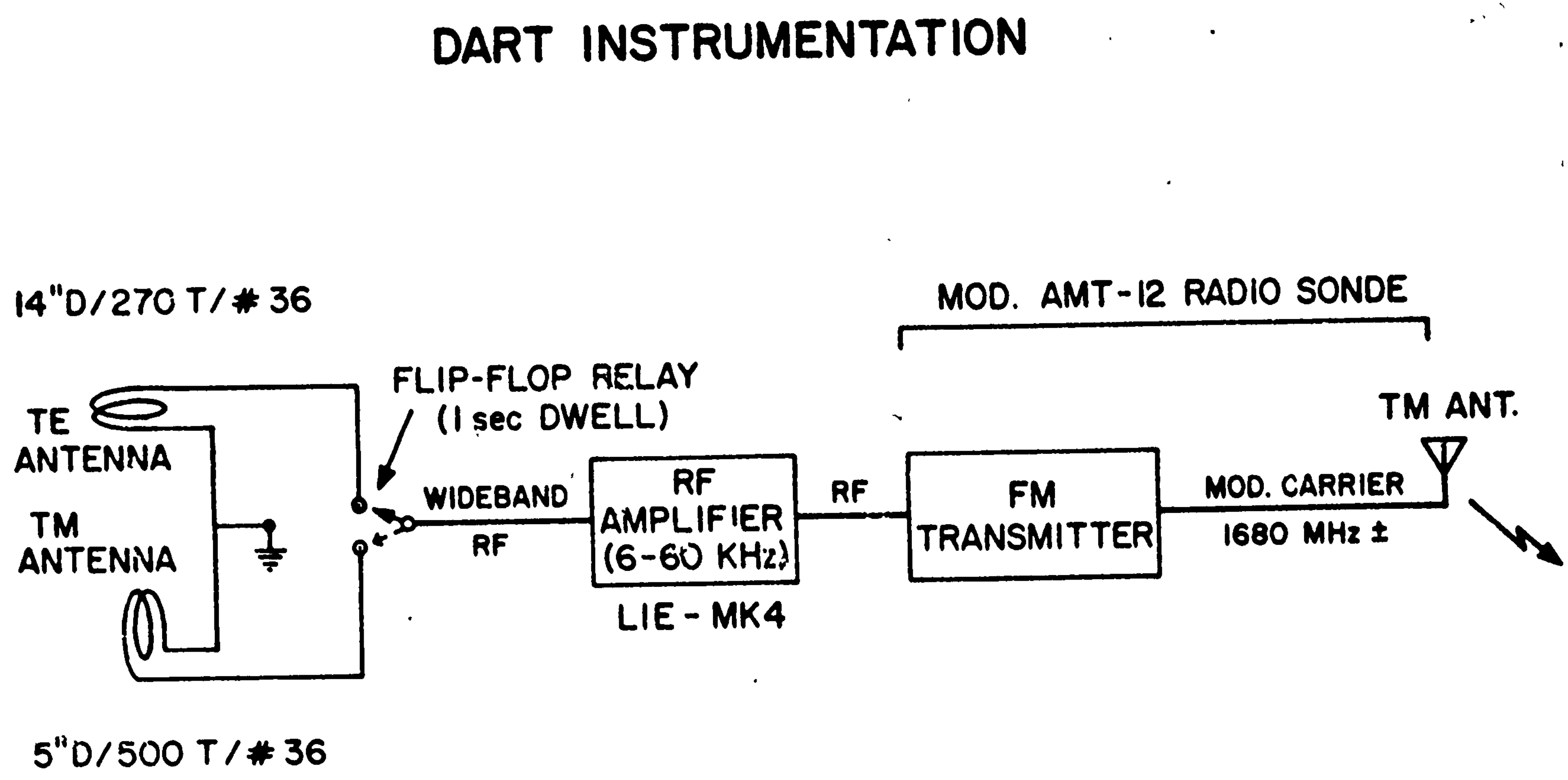

DART INSTRUMENTATION
14"D/270 T/# 36
TE ANTENNA
TM ANTENNA
5"D/500 T/# 36
FLIP-FLOP RELAY (1 sec DWELL)
WIDEBAND RF
RF AMPLIFIER (6-60 KHz)
LIE - MK4
RF
MOD. AMT-12 RADIO SONDE
FM TRANSMITTER
MOD. CARRIER
1680 MHz ±
TM ANT.

FIGURE 9.

RECEIVING/RECORDING INSTRUMENTATION

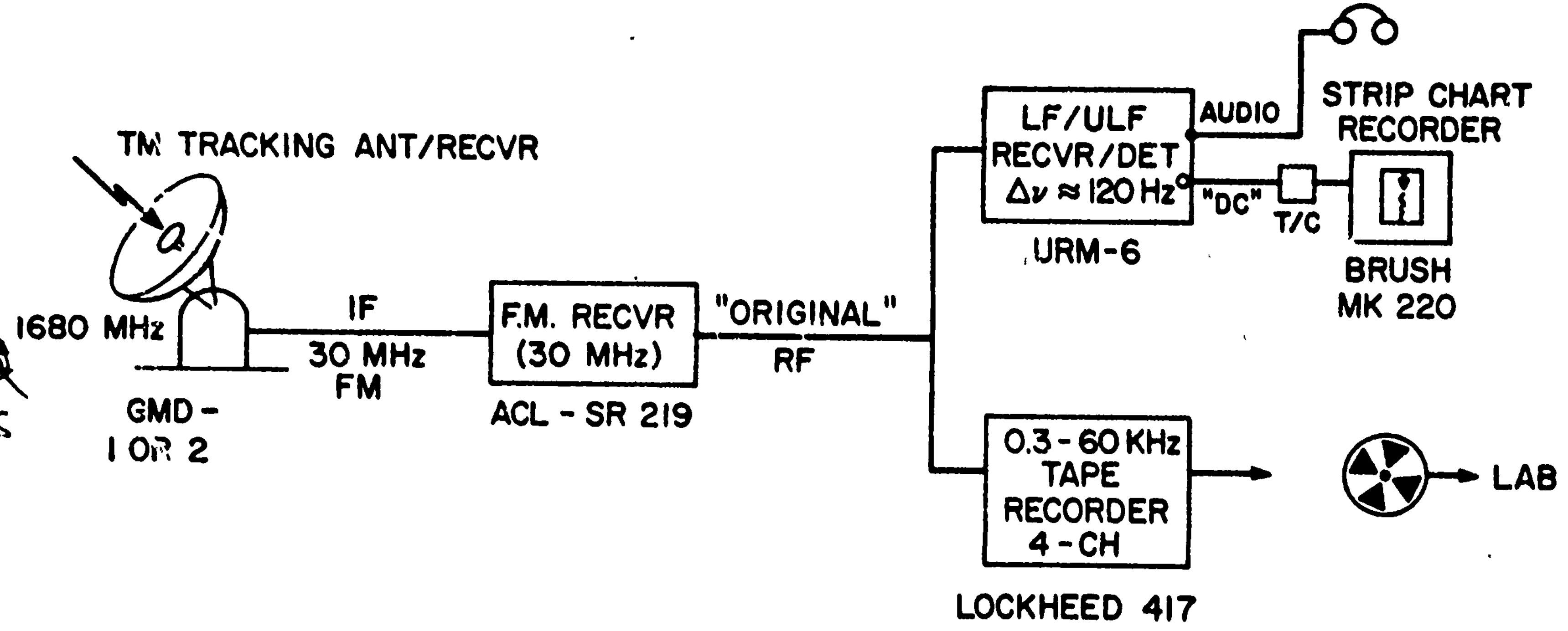
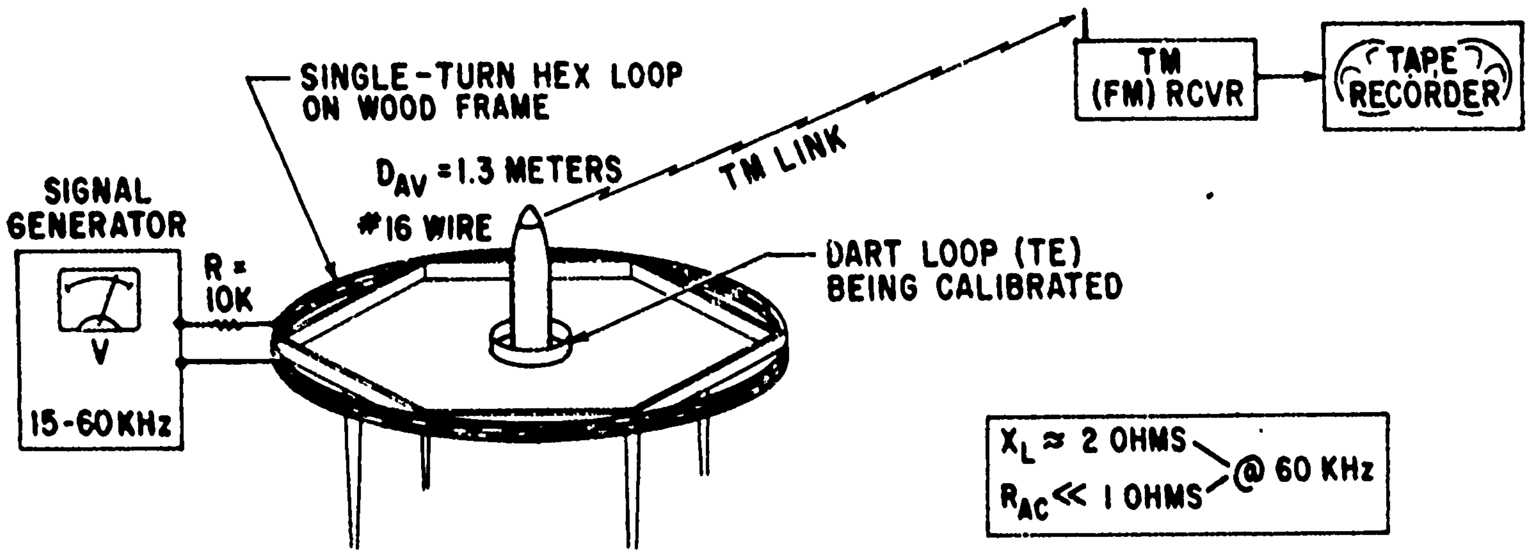


FIGURE 10.

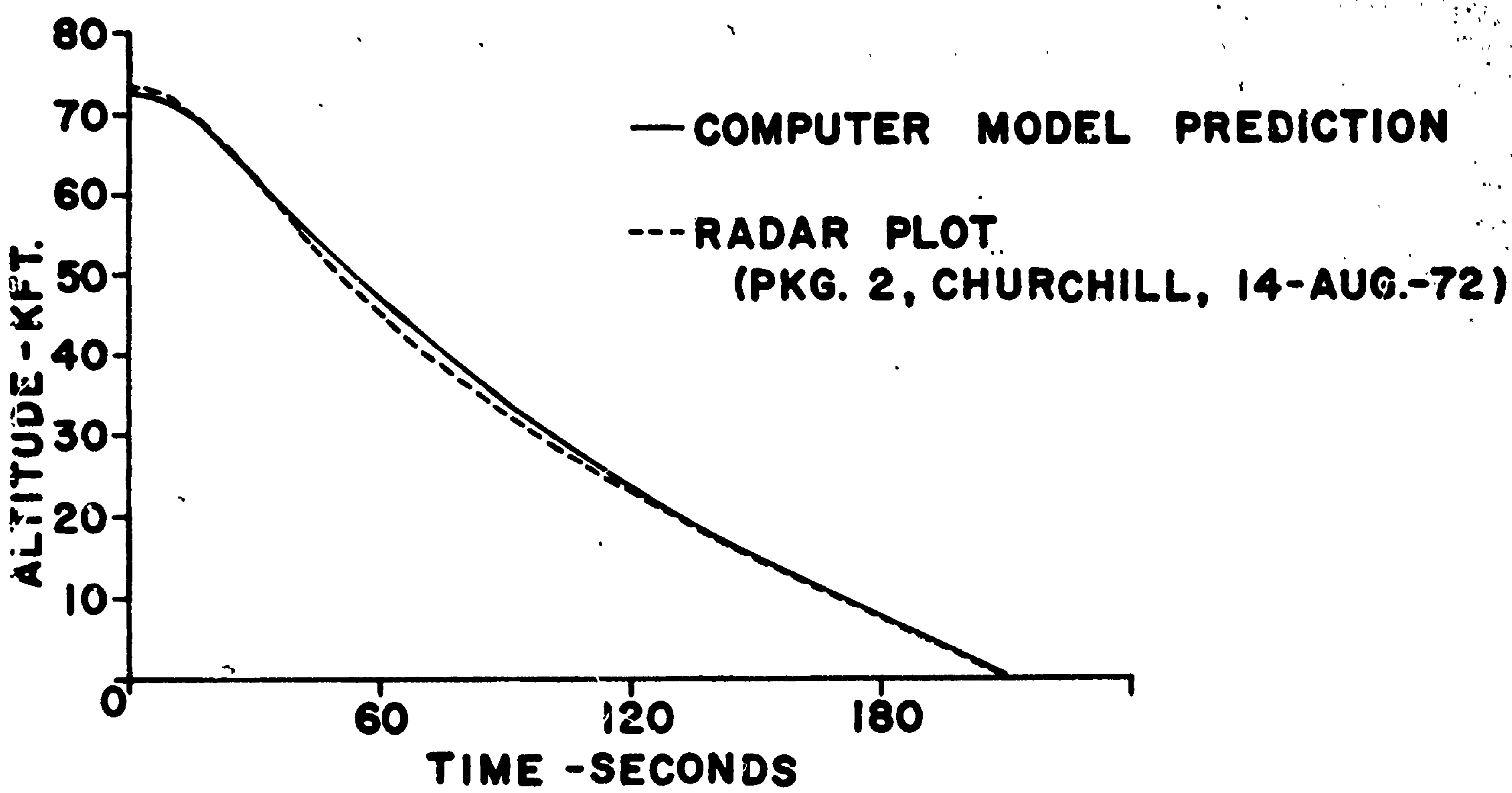
PRE-FLIGHT CALIBRATION



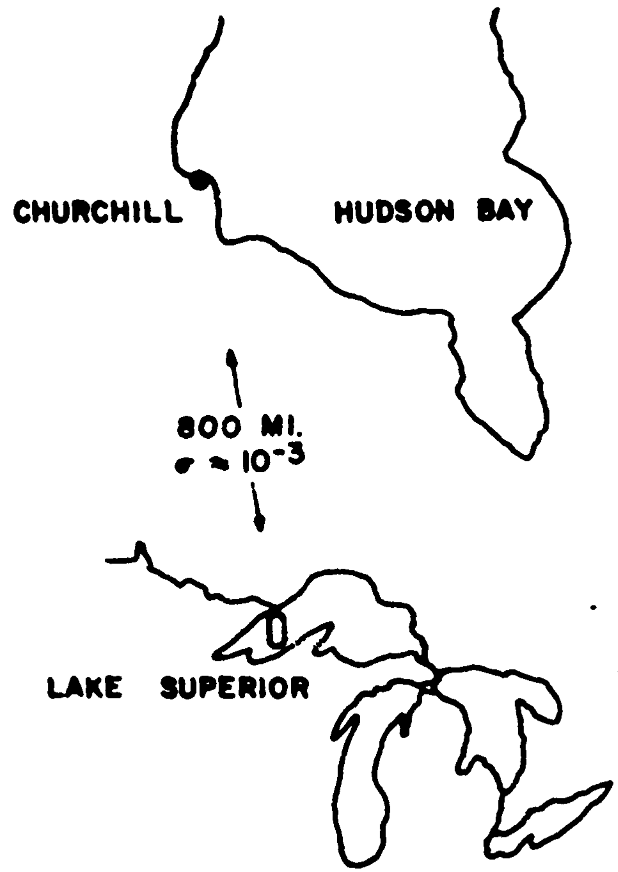
$$H = \frac{I}{D} \approx \frac{V}{RD} \quad \text{AMPERES/METER}$$

FIGURE 11.

ALTITUDE- TIME CURVES



LAKE SUPERIOR - CHURCHILL
14 AUGUST 1972



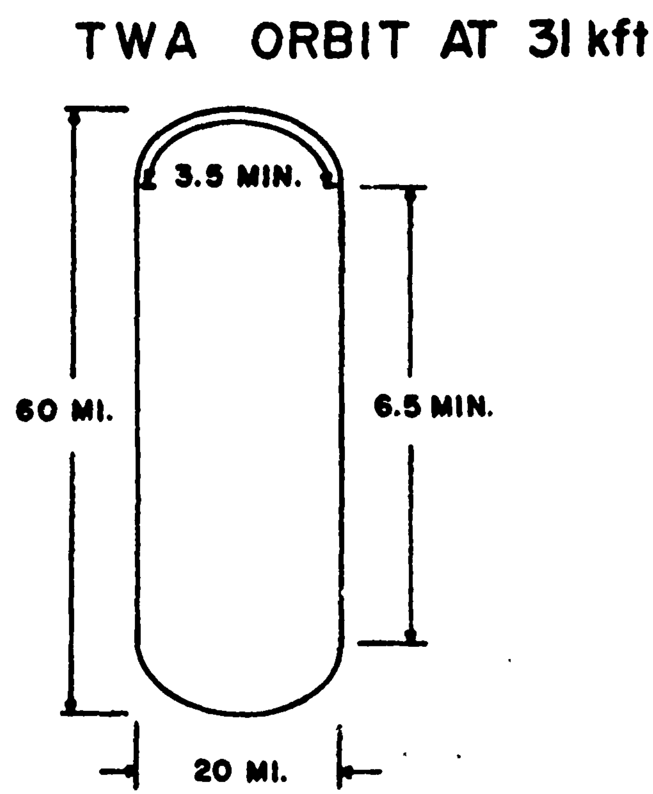


FIGURE 13.

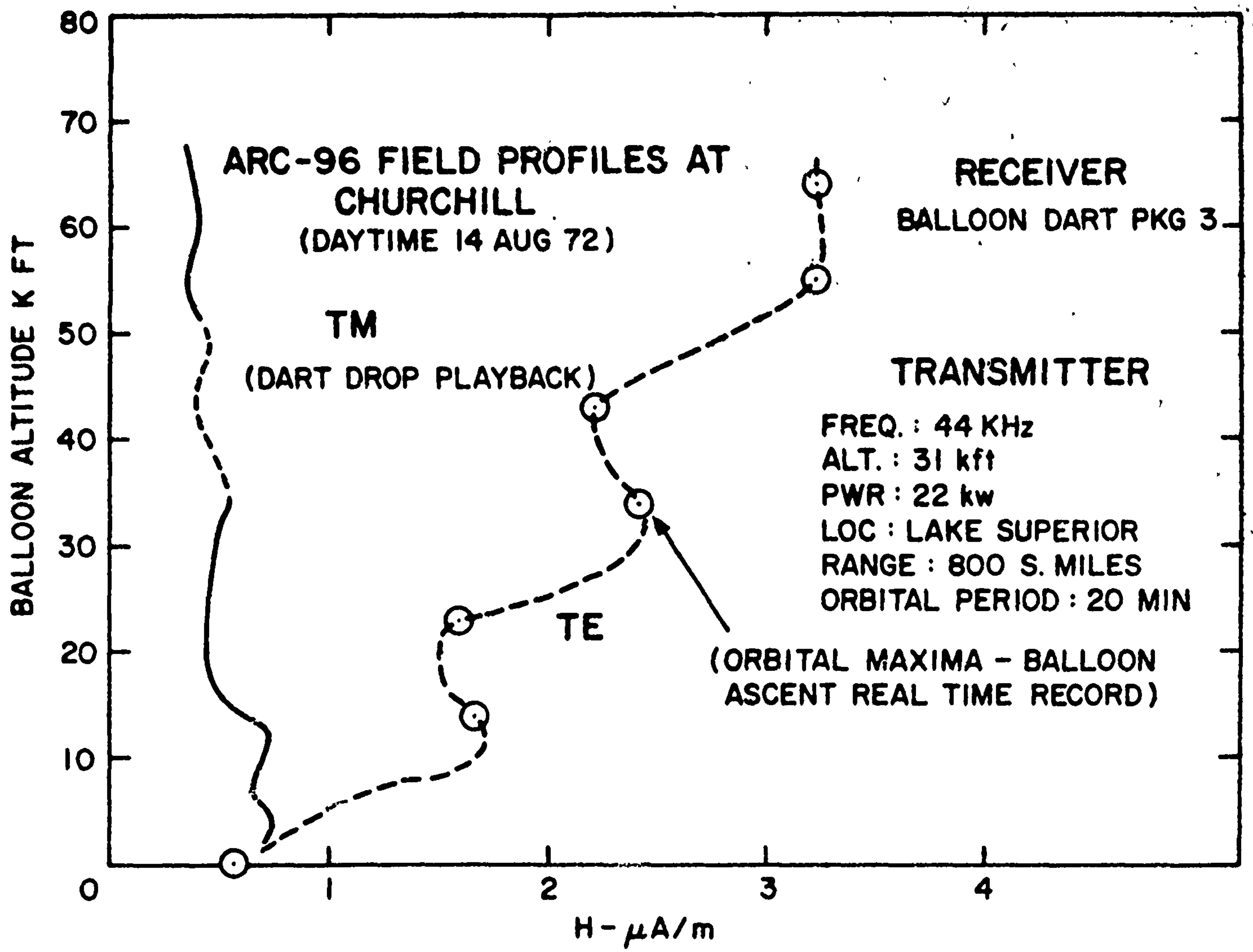
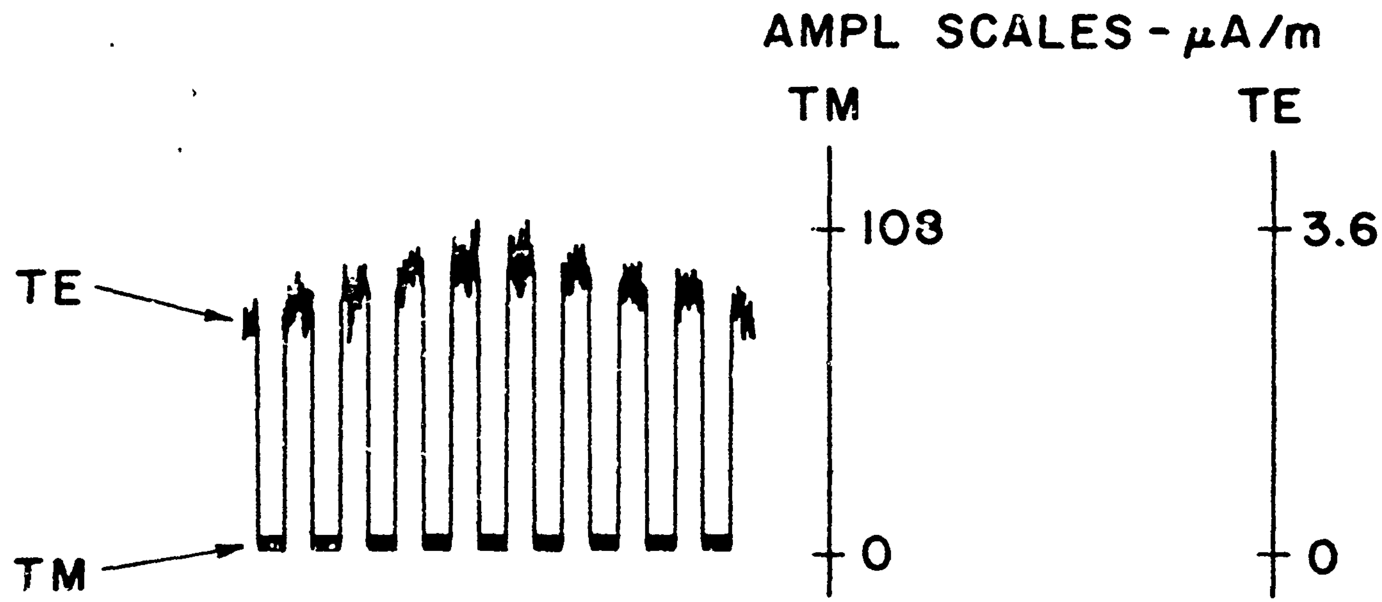

ARC-96 FIELD PROFILES AT CHURCHILL
(DAYTIME 14 AUG 72)
TM
(DART DROP PLAYBACK)
TE
RECEIVER
BALLOON DART PKG 3
TRANSMITTER
FREQ. : 44 KHz
ALT. : 31 kft
PWR : 22 kw
LOC : LAKE SUPERIOR
RANGE : 800 S. MILES
ORBITAL PERIOD : 20 MIN
(ORBITAL MAXIMA – BALLOON ASCENT REAL TIME RECORD)
BALLOON ALTITUDE K FT
0
10
20
30
40
50
60
70
80
1
2
3
4
H – μA/m

FIGURE 14.

SAMPLE OF CHURCHILL DATA
AT ONE GAIN LEVEL



UNITS OF H-AMPERES/METERS

IN FREE SPACE <u>ONLY</u>, E = 377 x H VOLTS/METER

FIGURE 15.

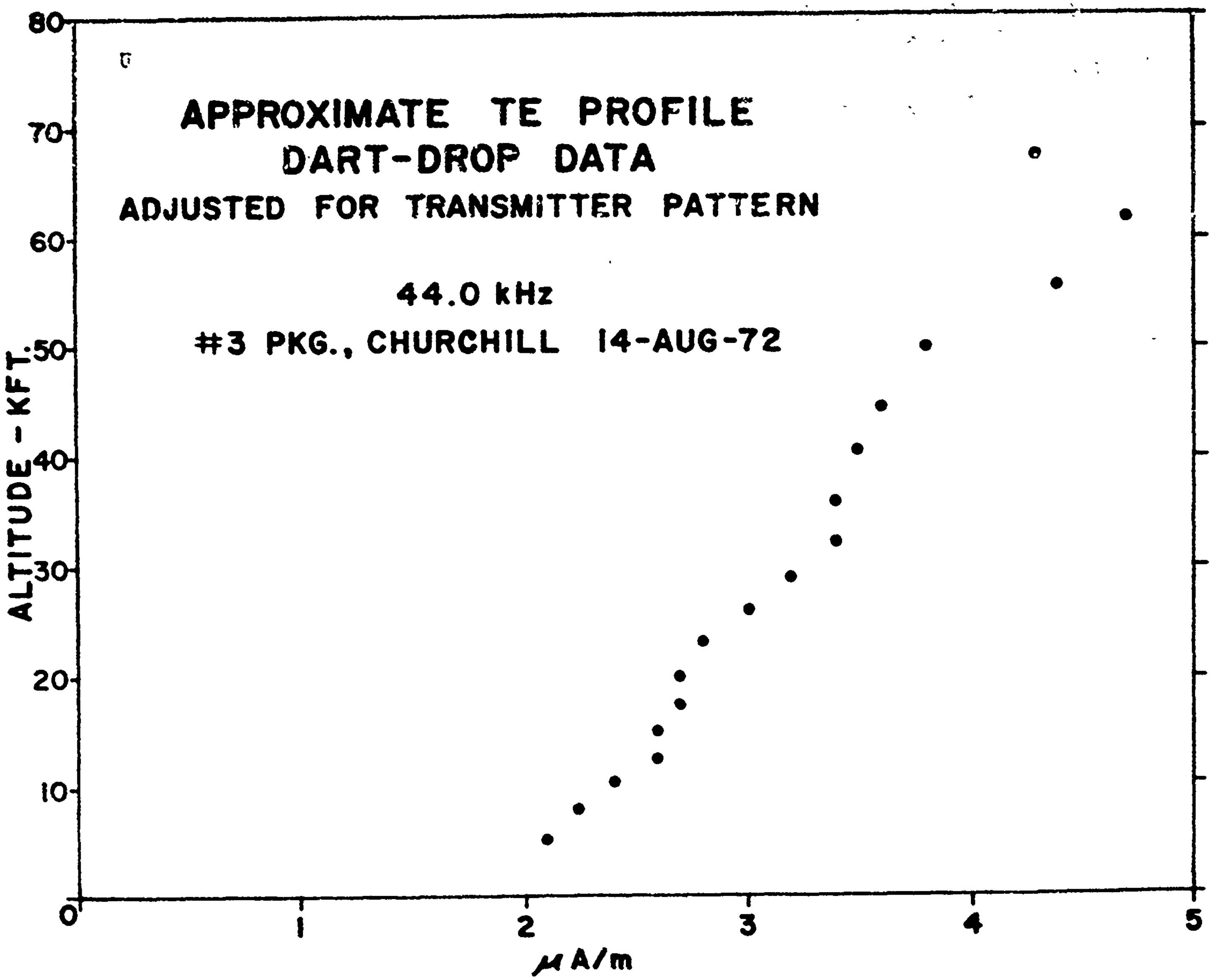

APPROXIMATE TE PROFILE
DART-DROP DATA
ADJUSTED FOR TRANSMITTER PATTERN
44.0 kHz
#3 PKG., CHURCHILL 14-AUG-72
ALTITUDE - KFT.
80
70
60
50
40
30
20
10
0
1
2
3
4
5
μ A/m

FIGURE 16.

APPROX. TE RADIATION PATTERN OF ARC-96

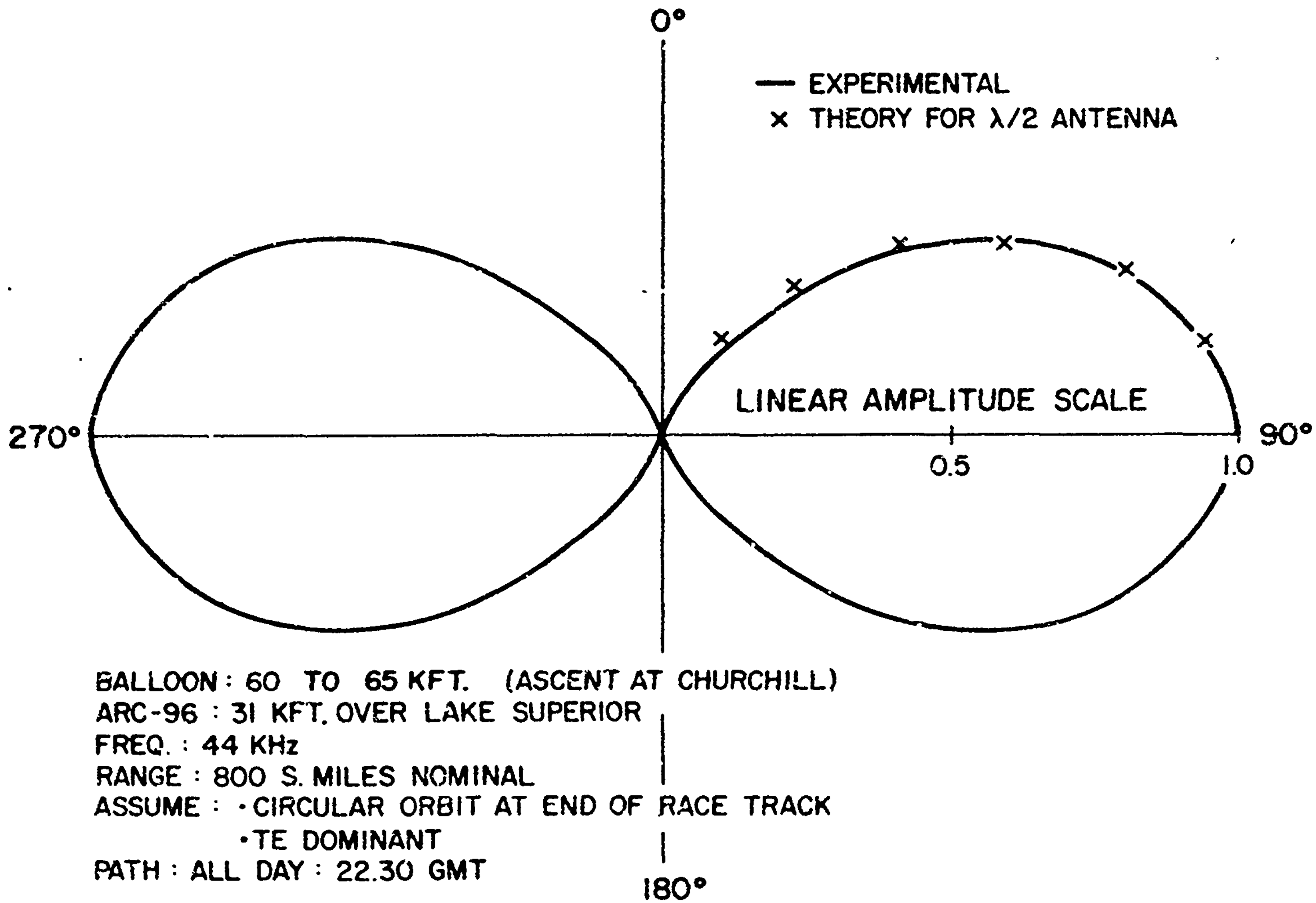
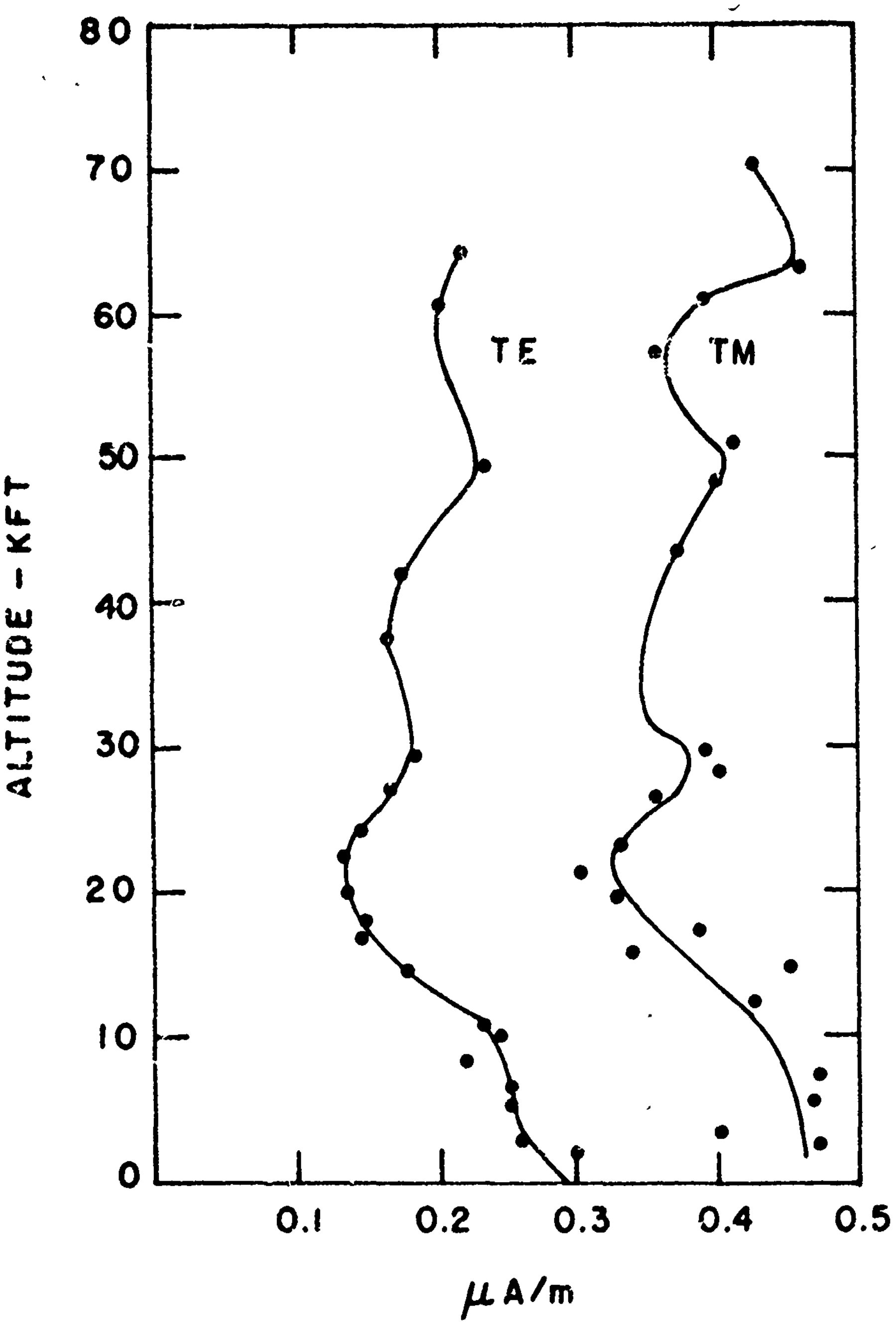


FIGURE 17.



PACKAGE 3 - CHURCHILL 14 AUG 72
TE & TM NOISE MEASURED AT 42KHz
DURING DART DROP BANDWIDTH ≈ 120Hz
T.C. 0.04 SEC AVG. TIME ≈ 2 SEC.

FIGURE 18.

SUMMARY CHURCHILL PKG #3

RECEIVER ALTITUDE	SIGNAL TE/TM	NOISE TM/TE	S/N
30,000'	14 DB	6 DB	20 DB
70,000'	19 DB	6 DB	25 DB

FIGURE 19.