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PROPAGATION MEASUREMENTS FOR OVER-WATER LOW-ANGLE AND OVER-HORIZON COMMUNICATIONS WITH BUOYS

FINAL REPORT

SEPTEMBER 1969

Prepared Under Contract Number N00014-68-C-0147

For

DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH
AERONAUTICS PROGRAMS
WASHINGTON, D. C. 20360

By

Francis P. Cullen

SANDERS ASSOCIATES, INC.

NASHUA, NEW HAMPSHIRE

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SUMMARY

This report describes the results of a program of measurement and analysis of radio frequency (RF) signal propagation. The work supplements previous parametric analysis and performance investigations related to over-water RF propagation.

The purpose of this program was to provide improved prediction of propagation loss on an over-water path. The primary application was over-horizon propagation using the surface-wave mode. Measurements were made to substantiate the propagation prediction procedures.

These over-water propagation measurements were made using buoys transmitting at 30.14 MHz, 173.5 MHz, and 406.5 MHz. The buoys were instrumented to telemeter buoy-attitude and vertical-acceleration data to the receiving station. This data and sea state conditions were used in the analysis of the measurements. Computer propagation prediction techniques were evaluated on the basis of these measurements. The 30 MHz measurements provided a measure of long range over-horizon propagation loss using the surface-wave mode. The measurements were made between Ft. Stark, New Hampshire and buoys moored about 6.5 nmi off the coast. Additional measurements to a range of 30 nmi were made from the U.S. Coast Guard Cutter Decisive.

The variation of measured signal levels were more extensive than anticipated, particularly under calm-sea conditions. The processing of recorded sensor data did not indicate a correlation between buoy location on wave crests and

troughs, and maximum and minimum signal strengths respectively. There was some evidence relating signal strength to a surface impedance which is dependent on sea conditions.

The received signal strengths were used to evaluate computer prediction methods. Signal variations under different sea conditions were used to estimate a compensating power margin for propagation calculations. The results were applied to design of a buoy transmitting over-horizon to distances of 200 nmi.

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SECTION 1
INTRODUCTION

This report describes a program of radio frequency propagation measurements and data analysis. The work was performed by Sanders Associates, Inc., for the Aeronautics Programs Branch of the Office of Naval Research, under Contract Number N00014-68-C-0147.

This measurement and analysis program is the third phase of an investigation of over-water low-angle and over-horizon radio frequency propagation. The findings are applicable to over-water communications between buoys and aircraft, buoys and ship, or similar sea environment applications. The first study phase* was a parametric analysis relating frequency, bandwidth, propagation mode, and other communication parameters to assist in optimizing communication design. The second study phase** examined component and interference factors relating to the design of a buoy system for the over-water communication application. These factors included an investigation of RF transmitter components, buoy power supplies, and interference conditions. A preliminary buoy design was presented to illustrate the application of the study material. In the present phase, the effects of varying sea conditions were used to calibrate the previous theoretical parametric treatment of communication link design. A revision of the previous buoy design has been made based on the study results.

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* "Over-Horizon Buoy Communication - Parametric Design Guide," Sanders Associates, Inc., December 1966, AD 815523.

** "Over-Horizon Sonobuoy Communications," Sanders Associates, Inc., April 1968, AD 389741, SAN-JNT-68-1902.

The primary objective of the measurement program was to clarify the effects of sea conditions on buoy communications. The buoy type investigated was a low profile type with close antenna coupling to the sea surface. Measurements were conducted between Fort Stark, New Castle Island, New Hampshire, and a buoy-mooring site located southwest of Star Island and northeast of White Island, Isles of Shoals.

The measurement program produced data on received signal strength and buoy attitude at frequencies of 30.14 MHz, 173.5 MHz, and 406.5 MHz under varying sea conditions. This data was compared with two computer programs for propagation analysis to determine if these programs can be calibrated to provide reliable predictions of buoy transmission performance.

This report is intended to be factual and provide detailed information on equipment types and procedure. Experience has shown that it is essential on a measurement project of this type to record in detail all aspects of the project. Otherwise, information is frequently lost and it becomes difficult if not impossible to reconstruct the actual data acquisition situation at a later date.

The initial phases of the project involved requests for frequency authorization and subsequent application for station licenses to the Federal Communications Commission (FCC). Authorization was requested for operation at frequencies of 8.35 MHz, 30.14 MHz, 173.5 MHz, 385.1 MHz and 406.5 MHz using both AM and FM modulations. After FCC approval of operating frequencies, buoy and shore-site transceivers were purchased. Three buoys were fabricated with transmitter frequencies of 30.14 MHz, 173.5 MHz and 406.5 MHz. These frequencies represent a spread across most likely future buoy operating bands and allowed frequency-dependent over-water propagation effects to be observed. All of the buoys contained acceleration and inclination sensors so that buoy attitude could be monitored. Each buoy was assigned a two-tone code which, when received and decoded in the buoy, started a three-minute transmission cycle. Buoy monitoring operations extended from free-floating buoy measurement in November, 1968 to measurements from moored buoys which lasted until May, 1969.

The data received from these buoys was recorded and analyzed to determine variations in received signal level as a function of sea state. The test range was 6.5 nmi in length and additional measurements were made to 30 nmi. These more extended measurements were made from a U.S. Coast Guard cutter and provided a longer range check on HF surface wave propagation.

The results of these measurements have been combined with previous aircraft measurements and theoretical analysis of sea state effects on propagation. The prime purpose was to establish the power margin necessary to assure reliable buoy communications under differing sea state conditions. This margin has been applied to the redesign* of a buoy communication system operating with an on-water aircraft via the surface-wave propagation mode.

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* op, cit - Over-Horizon Sonobuoy Communications Study, preliminary design of a buoy for operation using the surface-wave mode of propagation out to a range of 200 nmi.

SECTION 2
PROGRAM PLAN

2.1 TEST SITE

Tests were conducted between a receiving site at Ft. Stark, New Castle Island, New Hampshire, and buoys moored off White Island, Isle of Shoals. The distance between the receiving site and the buoys was 7.5 miles (6.5 nautical miles). Antennas were located on the top deck of a three story concrete blockhouse at Battery Kirk, Ft. Stark. An additional antenna, for measurement of HF surface-wave signals, was located at the shore.

The antenna elevations were 60 feet above sea level*. This elevation allows a line-of-sight radio range of 11 miles under normal (4/3 equivalent earth radius) refraction conditions. The transmission angle from the buoys to the shore receiving site was about 0.1 degrees. Operation at this low angle was necessary to explore the extent that waves would disrupt the line-of-sight transmission path.

Three buoys were moored off Star Island, in the channel between Star Island and White Island, Island of Shoals, New Hampshire. The buoys were moored in 100 to 130-feet of water. This particular position was selected because a rapid change in bottom contour was expected to produce good wave action. Also, the buoys and sea conditions at the mooring could be observed from the Coast Guard lighthouse at White Island.

The plans of the receiving site at Ft. Stark and the measurement range are shown in Figures 2-1 and 2-2.

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* Mean tide level 4 feet, mean high water 8.5 feet

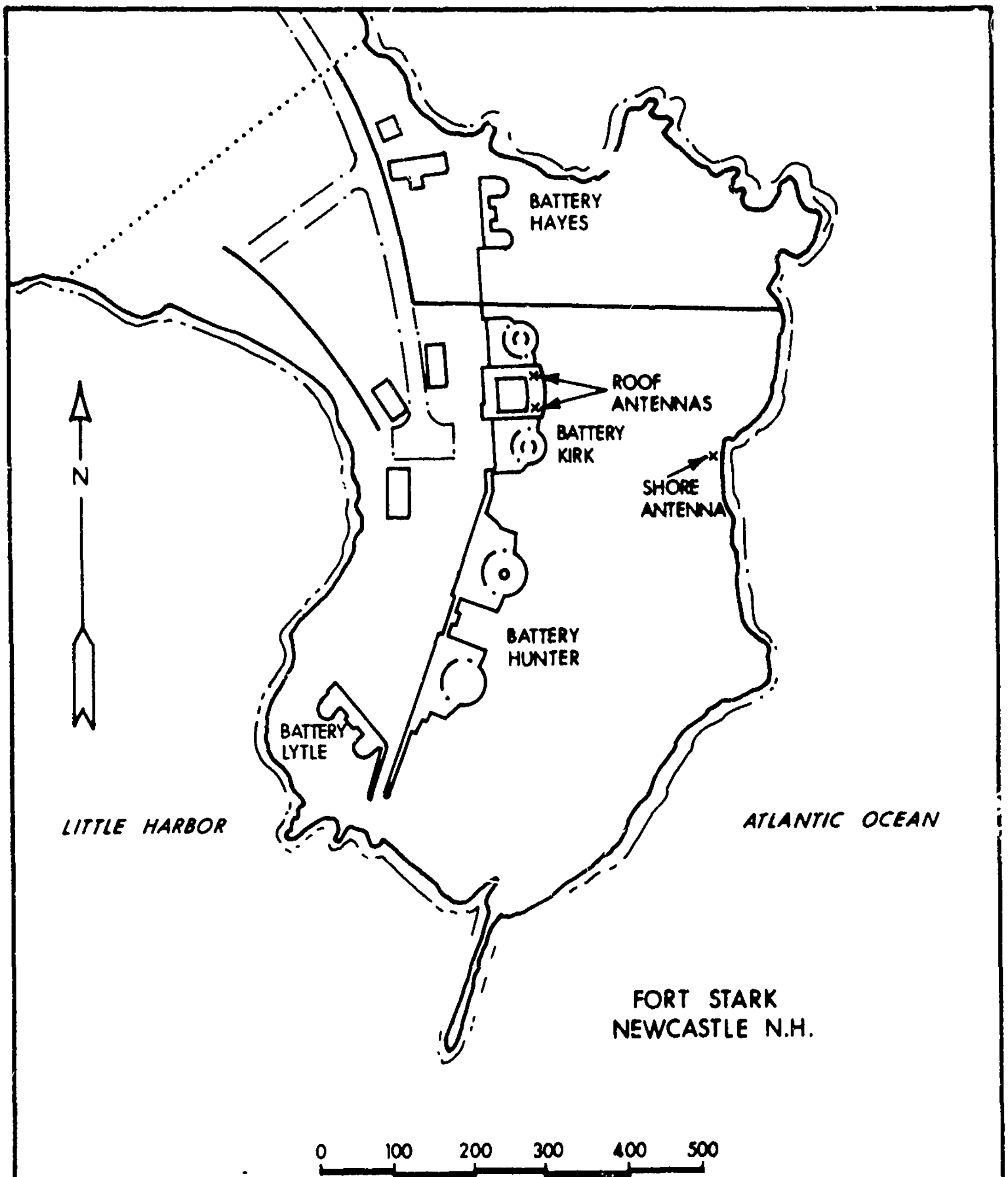

Figure 2-1. Receiving Site Plan

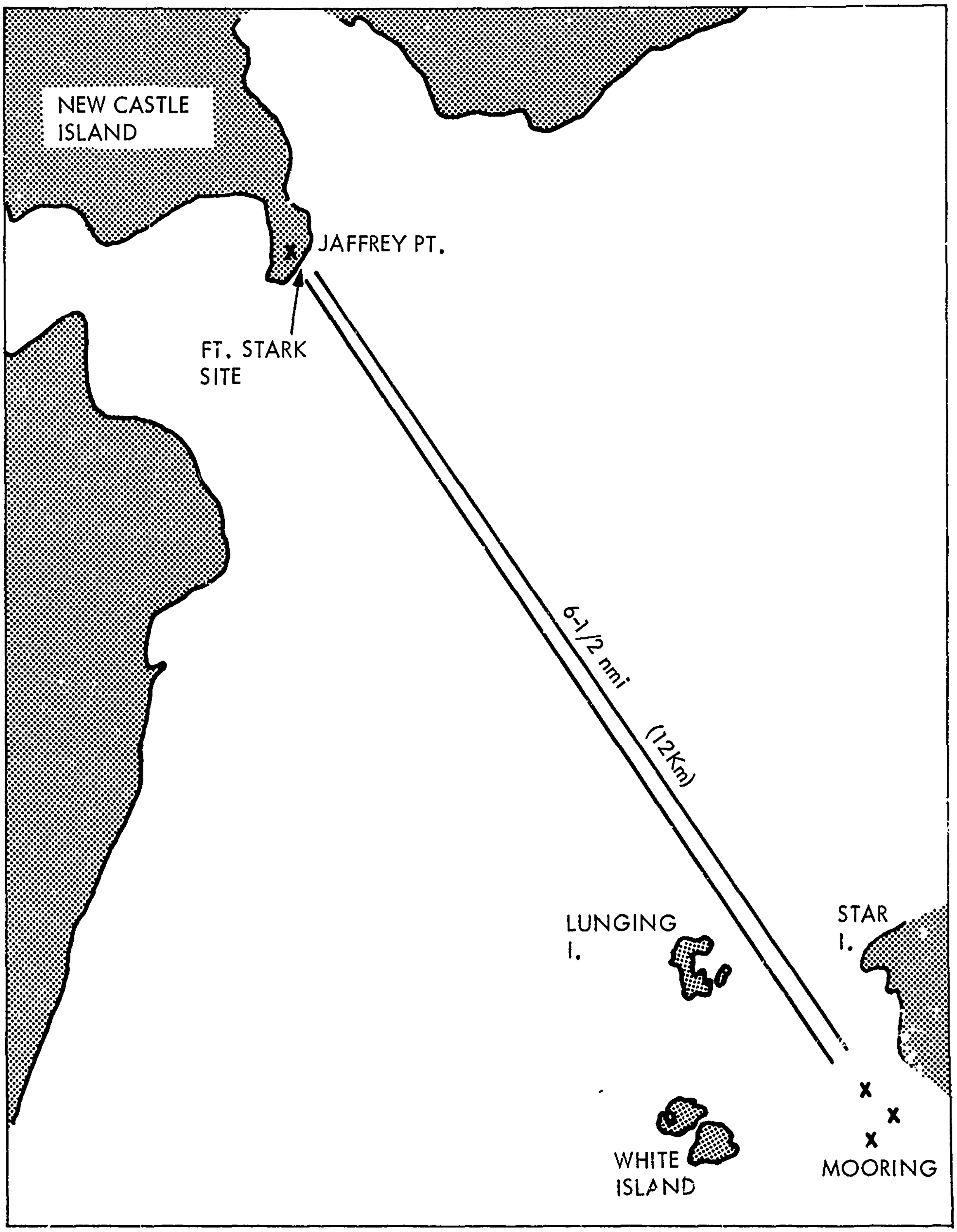

Figure 2-2. Measurement Range

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2.2 MEASUREMENT PROCEDURE

Three buoys, operating at frequencies of 30.14 MHz, 173.5 MHz, and 406.5 MHz, were moored. The buoys normally operated in the receive mode. Each receiver employed a tone decoder circuit and recognition of a specified two-tone sequence in the modulation of the received signal initiated a transmission cycle.

At the shore site, three transmitters with frequencies corresponding to the buoy frequencies were used. A command encoder was used to tone modulate the transmitter and any one of the three buoys could be commanded into the transmit mode. The transmission cycle from the buoy lasted about three minutes.

Each buoy was instrumented with an accelerometer and two inclinometers. The accelerometer provided a measure of vertical motion and the inclinometers, which were vertically positioned at a right angle to each other, measured the degree of buoy tilt.

Each of these sensors provided an output voltage proportional to the degree of displacement. These voltages controlled the output frequencies of three voltage controlled oscillators (VCO's) which operated at 400 Hz, 560 Hz, and 730 Hz. Provision was made for a fourth VCO, operating at 960 Hz, which could serve as a backup channel or be used to monitor ambient temperature. The VCO outputs were added and the composite frequency-division multiplexed signal used to modulate the buoy transmitter.

At the shore site, the received signals were demodulated and recorded on magnetic tape. The level of received signal strength was also monitored and recorded. A pen recorder was used to monitor selected channels.

Initial measurements were made under calm-sea conditions with free-floating buoys. These initial measurements allowed equipment performance to be checked out and provided data under Sea State 1/2 to Sea State 1 conditions.

The measurement routine required the buoys to be moored at the Isles of Shoals and to be interrogated from the Ft. Stark site. The frequency of interrogation was dependent on sea conditions. Since the effect of waves on RF propagation was of principle interest, the weather and sea state were the deciding factors in the rate and time of data acquisition.

The buoys were battery powered so that it was necessary to schedule a boat trip to the Isles of Shoals at about 4-day intervals to perform battery replacement. The buoys were removed from the water and taken to a nearby harbor for battery replacement. When the buoys had defective components or corroded connectors, they were taken ashore for repair and remoored on the subsequent trip.

Data was recorded at each of the three frequencies under varying sea states using antennas located on the roof of the Battery Kirk blockhouse. A fourth antenna was installed at the shore line to monitor the signal level due to surface wave propagation.

2.3 EQUIPMENT

2.3.1 CONFIGURATION

Shore Site

The operating set-up for the shore site is shown in Figure 2-3. Connections between each of the transceivers, the encoder, and the recorders were made manually for each frequency selection. The encoder has a 6-tone capability with any two of the following frequencies selectable:

592.5 Hz	847.5 Hz
637.5 Hz	937.5 Hz
757.5 Hz	802.5 Hz

Combinations of 592.5 Hz and 757.5 Hz were used for the 30.14 MHz transmitter code, 592.5 Hz and 937.5 Hz for the 173.5 MHz transmitter code, and 802.5 Hz and 847.5 Hz for the 406.5 MHz code. A command switch located on the encoder produced an output of 1-second duration of the first tone selection followed by a continuous second tone output until the switch was released. These

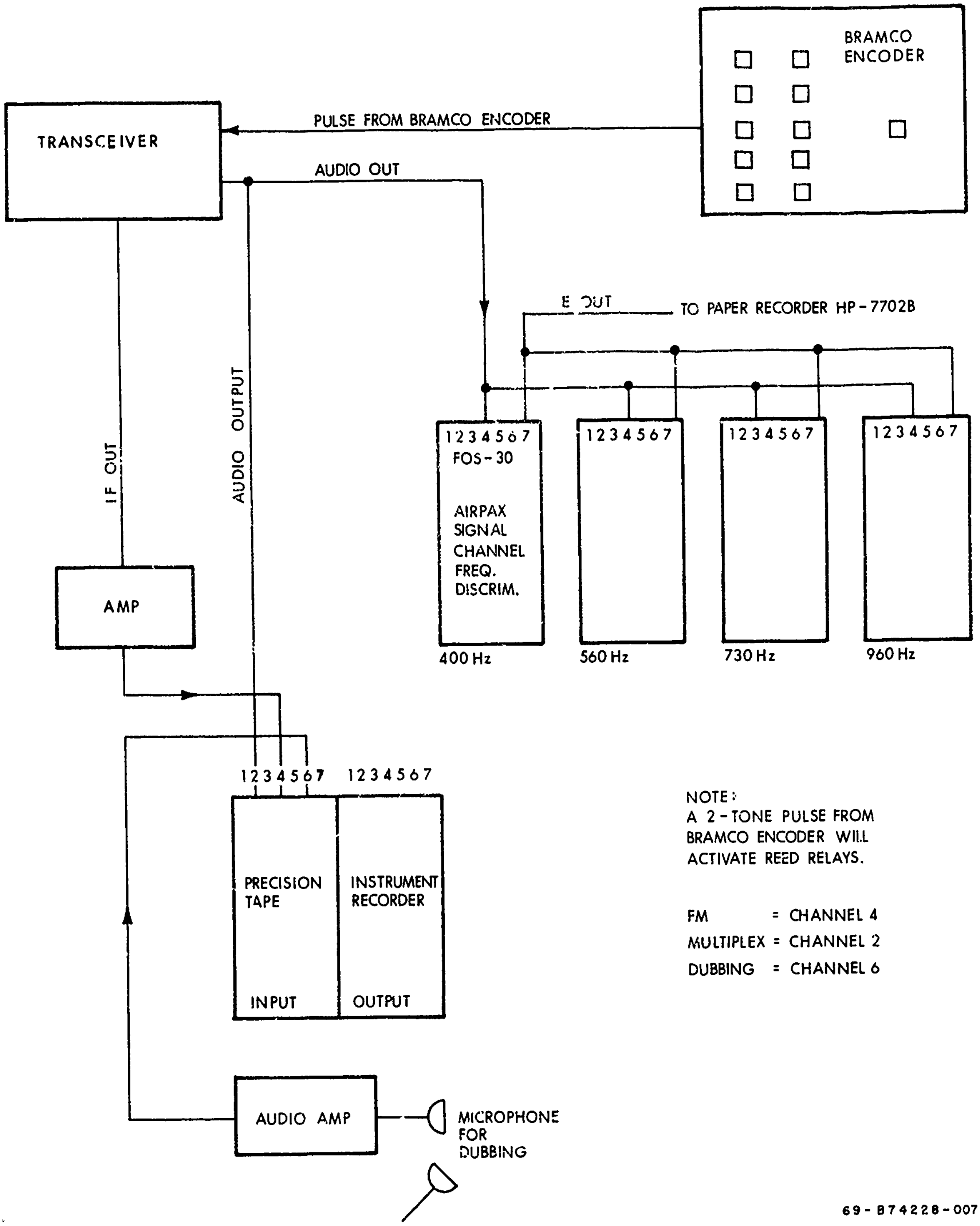

Figure 2-3. Shore Site Equipment

tones modulated the transmitter and the reception of the transmitted signal by the buoy receiver having a corresponding frequency caused the buoy to switch to a transmit mode. This signal transmitted from the buoy was in turn received by the shore site transceiver. The intermediate frequency (IF) level prior to the first limiter was amplified, detected, and recorded on Channel 4 of the magnetic tape recorder. This IF level data was later converted to equivalent field strength at the receiver input. The audio output containing the multiplexed sensor signals was recorded on Channel 2 of the magnetic tape recorder. The audio amplifier was used to monitor the recorded data and to dub verbal descriptions of test conditions on Channel 6 of the recorder. Alternately, the audio output was connected to the subcarrier discriminators so that any two of the demodulated sensor voltages could be displayed on the paper recorder. The IF signal level also could be selected for display.

Antennas for 30.14 MHz, 173.5 MHz, and 406.5 MHz were located on the top deck of the Battery Kirk blockhouse. A quarter-wave monopole (7.5 ft) antenna, with four rods providing a radial ground plane, was used for 30.14 MHz transmission. This antenna was connected to the HF transceiver located on the deck below through 45 ft of RG-8/U coaxial cable. An alternate antenna for operation at this frequency was located at the shore line about 300 ft in front of the blockhouse. This antenna was a monopole antenna using a folded dipole as the radiating element, a single director element, and a radial ground system consisting of two parallel rods. The antenna was connected to the HF transceiver at the blockhouse through 330 ft of RG-8/U coaxial cable.

The antennas for VHF and UHF operations were located on the upper deck of the blockhouse. The 173.5 MHz antenna was an 8-element Yagi antenna connected to the VHF transceiver through 45 ft of RG-8/U coaxial cable. The 406.5 MHz antenna was a "bow-tie" dipole element with a corner reflector and was connected to the UHF transceiver through 45 ft of RG-8/U coaxial cable. Photographs of the antenna installations are shown in Figures 2-4 and 2-5.

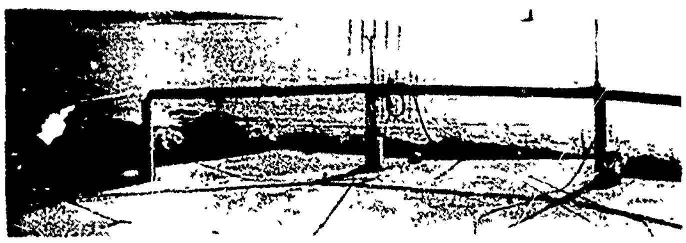

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Figure 2-4. Roof Antenna Installation

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Figure 2-5. Shore Antenna Installation

Buoys

The connections of the electronic components located within the buoys are shown in Figure 2-6. Three similar configurations were fabricated. The common configuration for all buoys used a vertical accelerometer and two inclinometers. The inclinometers were fabricated from linear potentiometers which used weighted moment arms to obtain shaft rotation as a function of buoy tilt. These sensors provided a voltage to the voltage controlled oscillators (VCO's). The varying frequency outputs of the VCO's were summed and used to modulate the transmitter section of the transceiver during the transmission period. The receiver section contains a tone decoder. In each of the transceivers, these tone decoders had different 2-tone combinations of reed relays which were activated when the correct tones were present in the demodulated signal. The decoder output activated the timer circuit which, in turn, closes the control relay contacts. Voltage was applied to the sensors, VCO's and transmitter control relay. Power was obtained from two 12-volt nickel-cadmium battery packs having a 10 to 12 ampere-hour capacity, and from three alkaline bias batteries.

The HF buoy antenna was a loaded monopole antenna which was 40 inches long. The VHF buoy antenna was a quarter-wave monopole and the VHF buoy antenna was a five-eighths wave monopole antenna.

2.3.2 RANGE CALIBRATION

All subsequent calculations will require correction of measured levels to account for line loss and antenna gains. Antenna gains were referenced to a Stoddart dipole antenna of the type used for RFI specification measurements. The Fort Stark antenna gains were measured on-site. The buoy antenna gains were measured ashore. Each buoy had a ground plane screen extending over its surface. This screen was sufficiently large so that gain measurements, with the buoys out of the water, were believed to be representative.

The HF (30.14 MHz) and VHF (173.5 MHz) antenna cables were type RG-8/U and the UHF (406.5 MHz) antenna cable was type RG-8/U. The antenna and cable characteristics are listed in Table 2-1.

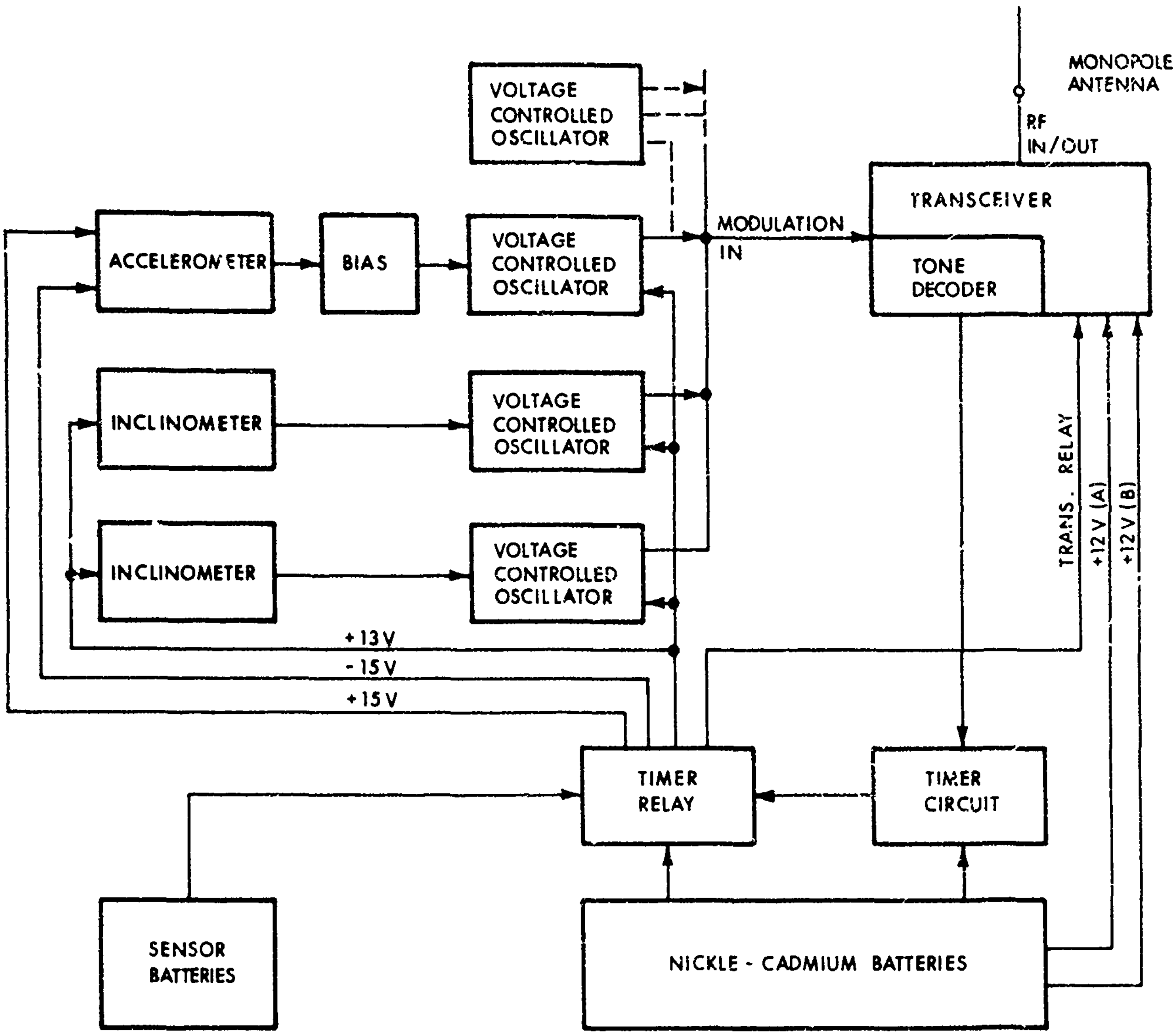

Figure 2-6. Buoy Electronic Components

TABLE 2-1

ANTENNA AND CABLE CHARACTERISTICS

CHANNEL & RECEIVER	CABLE TYPE AND LENGTH	CABLE LOSS	ANT. TYPE	ANT. GAIN*	BUOY ANT. TYPE	BUOY ANT. GAIN*	BUOY TRANS.
30.14 MHz (roof ant.) ER-43-A	RG-8/U 45'	0.9 dB	monopole with four radials	-2 dB	monopole with ferrite slug loading	-10 dB	ET-61-A
30.14 MHz (shore ant.) ER-43-A	RG-8/U 330'	4.0 dB	monopole cardioid	+1 dB	monopole with ferrite slug loading	-10 dB	ET-61-A
173.5 MHz ER-44-A	RG-8/U 45'	2.3 dB	folded monopole w/director and radials	+1.2 dB	quarter-wave monopole	-1.5 dB	ET-62-A
406.5 MHz ER-53-A	RG-8/U 45'	3.9 dB	bow-tie corner reflector	+6.5 dB	five-eighths wave monopole	-1.5 dB	ET-88-A

*Referenced to dipole

2.3.3 RADIO STATION AUTHORIZATION

To perform this measurement program it was necessary to request authorization for radio transmitters from the Federal Communications Commission. Licenses were requested for operation in the experimental radio service at frequencies of 30.14 MHz, 173.5 MHz, and 406.5 MHz. Both fixed-station and mobile licenses were requested. In addition, authorization also was requested for operation at frequencies of 8.350 MHz and 385.1 MHz; however, these frequencies were not used during the measurement program.

In response to our request, the Federal Communications Commission issued the Experimental Radio Station licenses listed in Table 2-2 below.

TABLE 2-2

EXPERIMENTAL RADIO STATION LICENSES

Location	Status	Frequency	Emission Designator	Authorized Power (watts)	Call Sign
Ft. Stark	Fixed	8350 kHz 406.5 MHz	3F9 12F3, 12F9	25(ERP) 10(ERP)	KB2XHL
Ft. Stark	Fixed	30.14 MHz 173.5 MHz 385.1 MHz	12A3, 12F3, 12F9 12F3, 12F9 12F3, 12F9	10(ERP) 10(ERP) 10(ERP)	KB2XGS
Within 15 Miles of Ft. Stark	Mobile	8350 kHz 406.5 kHz	3F9 12F3, 12F9	25(ERP) 25(ERP)	KB2XHK
Within 15 Miles of Ft. Stark	Mobile	30.14 MHz 173.5 MHz 385.1 MHz	12A3, 12F3, 12F9 12F3, 12F9 12F3, 12F9	10(ERP) 10(ERP) 10(ERP)	KB2XHJ

SECTION 3

DATA ACQUISITION

3.1 MEASUREMENT CONDITIONS

The technical objective of this project was to obtain signal strength measurements from buoys operating at three different frequencies under a variety of sea conditions. These sea conditions were expected to range from Sea State 1/2 to Sea State 4 or higher in the Portsmouth, New Hampshire area during the winter months. The data resulting from these measurements was to be processed and used for prediction of over-sea propagation loss.

3.1.1 BUOYS

Two buoy configurations were used. One type was discus shaped with a double parabolic cross-section. The buoy diameter was 56 inches and the thickness was 24 inches. This buoy is shown in Figure 3-1. The other type buoy used resembled a beer keg with a slight side curvature. The height of this buoy was 24 inches and the diameter 20 inches. This buoy is shown in Figure 3-2. (Note: Formation of ice on buoys did not affect their performance.)

The discus shaped buoy was essentially a wave-follower with moderate small-angle tilting under choppy sea conditions. The keg-shaped buoys behaved in a manner similar to that expected for spherical buoys. Since the behavior was similar, the use of the keg shape provided a more compact buoy for housing the required axially-installed rectangular instrument package. The amount of freeboard and resulting buoy motion in choppy seas was controlled by the number of weights used on the buoy.

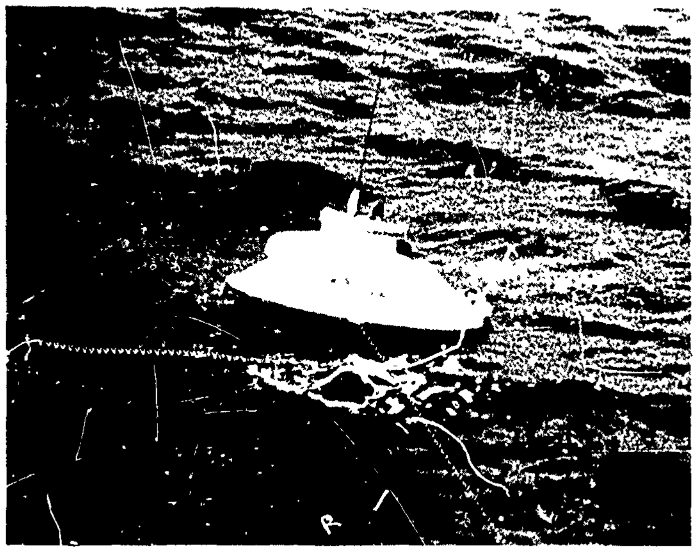

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Figure 3-1. Discus-shaped Buoy.

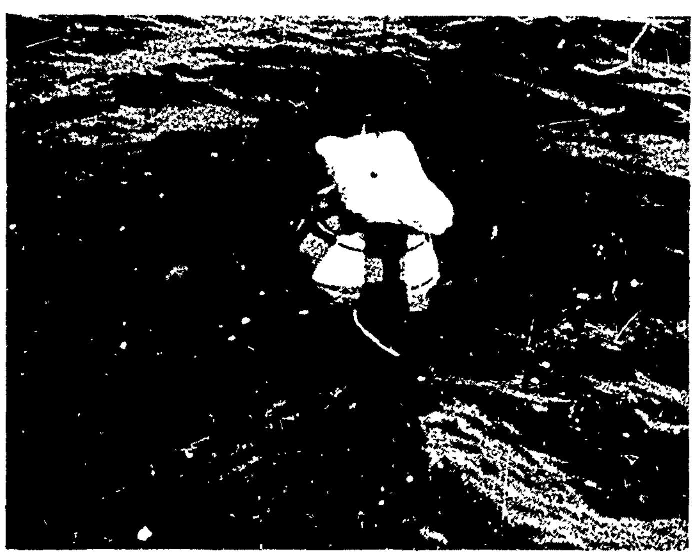

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Figure 3-2. Keg-shaped Buoy

3.1.2 MOORINGS

After a preliminary period of measurements on free-floating buoys and from buoys at Gossport Harbor*, permanent moorings were established in the channel southwest of Star Island and northeast of White Island. (It was necessary to obtain a Coast Guard authorization for these moorings.) Hardware used in the moorings included wire cable, subsurface floats to prevent the cable from becoming entangled on bottom obstructions and 100 to 150 lb granite anchors.

Changing batteries and servicing the buoys was necessary on the average of every four to five days. When buoys were taken ashore for more extensive maintenance, surface floats were attached to hold the moorings. During one storm that occurred in the month of February, three moorings were lost and new moorings had to be established at the end of the storm period.

3.1.3 WEATHER CONDITIONS AND SEA STATE

Measurements made during late in the months of November and December provided data on calm (Sea State 1/2 to Sea State 1) sea conditions at the HF (30.14 MHz) and VHF (173.5 MHz) frequencies. The UHF buoy was not available until January. Once the basic reference data at calm sea conditions was acquired at all frequencies, an effort was made to coincide subsequent measurements** with weather conditions favorable to higher sea states. Weather became a major factor in scheduling buoy measurements. The significance of wind speed and wind duration is indicated on the chart of Figure 3-3. A Sea State 3 (SS3) condition is developed by 12 to 15 mile-an-hour winds occurring for ten hours or more over a fetch of about 100 miles. At the Fort Stark location, the wind would have to come from the east or preferably from the northeast to develop SS3 conditions.

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* Northeast side of Star Island, Isle of Shoals.

** It should be noted that battery capacity was directly dependent on the number of transmission cycles. As a result the number of calm sea buoy interrogations was restricted to prolong the effective operating time of the buoy receiver.

WIND WAVES AT SEA

1	WIND VELOCITY KNOTS	4, 5, 6, 7, 8, 9, 10, 20, 30, 40, 50, 60, 70
2	BEAUFORT WIND AND DESCRIPTION	1 LIGHT AIR; 2 LIGHT BREEZE; 3 GENTLE BREEZE; 4 MODERATE BREEZE; 5 FRESH BREEZE; 6 STRONG BREEZE; 7 MODERATE GALE; 8 FRESH GALE; 9 STRONG GALE; 10 WHOLE GALE; 11 STORM
3	REQUIRED FETCH IN MILES — FETCH IS THE NUMBER OF MILES A GIVEN WIND HAS BEEN BLOWING OVER OPEN WATER	50, 100, 200, 300, 400, 500, 600, 700
4	REQUIRED WIND DURATION IN HOURS — DURATION IS THE TIME A GIVEN WIND HAS BEEN BLOWING OVER OPEN WATER	5, 20, 25, 30, 35
	IF THE FETCH AND DURATION ARE AS GREAT AS INDICATED ABOVE, THE FOLLOWING WAVE CONDITIONS WILL EXIST. WAVE HEIGHTS MAY BE UP TO 10% GREATER IF FETCH AND DURATION ARE GREATER.	
5	WAVE HEIGHT CREST TO TROUGH IN FEET	2, 4 WHITE CAPS FORM, 6, 8, 10, 15, 20, 25, 30, 40, 50, 60
6	SEA STATE AND DESCRIPTION	1 SMOOTH; 2 SLIGHT; 3 MODERATE; 4 ROUGH; 5 VERY ROUGH; 6 HIGH; 7 VERY HIGH; 8 PRECIPITOUS
7	WAVE PERIOD SEC.	2, 3, 4, 6, 8, 10, 12, 14, 16, 18, 20
8	WAVE LENGTH FEET	20, 40, 60, 80, 100, 150, 200, 300, 400, 500, 600, 800, 1000, 1400, 1800
9	WAVE VELOCITY KNOTS	5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60
10	PARTICLE VELOCITY FEET/SEC.	2, 3, 4, 5, 6, 8, 10, 12, 14
11	WIND VELOCITY KNOTS	4, 5, 6, 7, 8, 9, 10, 20, 30, 40, 50, 60, 70

This table applies only to waves generated by the local wind and does not apply to swell originating elsewhere

WARNING Presence of swell makes accurate wave observations exceedingly difficult

NOTE: (a) The height of waves is arbitrarily chosen as the height of the highest 1/3 of the waves. Occasional waves caused by interference between waves or between waves and swell may be considerably larger.

(b) Only lines 7, 8, and 9 are applicable to swell as well as waves.

(c) The above values are only approximate due both to lack of precise data and to the difficulty in expressing it in a single easy way.

(d) Below the surface the wave motion decreases by 1/2 for every 1/9 of a wave length of depth increase.

(e) Observations and comments leading to increased accuracy and usefulness are desired.

Publication suggested by J. [illegible] General Electric Advanced Technology Lab., Schenectady, N.Y.

Reprinted from Vine and Volkmann, Woods Hole Oceanographic Institution, June 19[illegible]

69-874228-015

Figure 3-3. Wind Waves at Sea

For the purposes of these tests, a 3- to 5-foot effective wave height, which is indicative of SS3, could also develop by a combination of 2- to 3-foot swells and 2- to 3-foot waves. This condition was reasonably common during the winter months. However, SS4 and particularly SS5 occurred only under more severe weather conditions. The SS5 conditions are generated by 20 to 25-mile-an-hour winds for periods greater than 25 hours over a 200-mile fetch. These conditions were less common and required considerable observation of the weather and planning of buoy refurbishing cycles.

The most promising condition for generation of rough-sea conditions in the Portsmouth area is the passage of a low-pressure area across southern New England. The associated counter-clockwise wind pattern produces the northeast winds needed to generate the high waves. Normally, the storm track identified by the passage of successive low pressure areas is across southern Canada in December and January and continues to move south in the succeeding months. This was the condition which prevailed during the test period.

Through January, the sea states range from calm to SS3. The winds were generally from the west, up to 15 to 25 miles-an-hour. Since a long fetch was not present, the roughest seas encountered were composed of swells and 2- to 3-foot wind-generated waves.

During February, a number of successive lows passed over New England and held positions off the coast. This resulted in high sea conditions during most of the month. Because of these conditions, it was not feasible to replace batteries and remoor the buoys during a continuous 3-week period. The first SS5 condition occurred in the middle of this period. In late February and March. the storms were spaced so that boat operations were reasonable and measurements were made in conditions from SS3 to measurements at HF in SS5 conditions. Measurements were continued until early May.

3.1.4 EXTENT OF MEASUREMENT CONDITIONS

Initially, measurements were made at each of the three frequencies under SS1/2 conditions. Under rougher sea conditions, it becomes difficult to precisely classify the sea state. The table by Vine and Volkmann, Figure 3-3, is helpful but the presence of swells and multiple wave systems makes most attempts at describing a sea as SS3 rather than SS4 an arbitrary choice. This may be illustrated by a comparison of estimates of sea conditions. Our reference on sea conditions during measurements was based on visual observations from the Coast Guard lighthouse at White Island. On one particular day when lighthouse personnel reported 1- to 2-foot waves, the work boat in the area of the buoys reported 3- to 4-foot waves. The contribution of swell may explain the difference in estimates. The difficulty in making visual estimates of sea conditions is discussed and the recommended procedures are described in a report by Pierson*. To some extent the accelerometer range and period may help in estimating sea conditions but, in the final analysis, measurement conditions will be described as either calm (SS1/2 to SS1), moderate (SS3), or heavy (SS5). A more definative determination of sea conditions would imply a greater precision to the measurements than justified by the monitoring techniques.

Data was acquired at all frequencies from the buoys under calm and moderate sea conditions. Only HF data was obtained under SS5 conditions.

3.2 DATA ANALYSIS

The primary objective of the data acquisition and analysis was to determine a design margin for buoy transmitter power. This margin must account for the effects of high-sea conditions on low-angle and over-horizon propagation modes.

While determining the power margin, the data analysis will be directed towards isolating the contributions of factors such as buoy tilt, wave effects, and refractive conditions.

3.2.1 SEA SURFACE CONDITIONS

Sea surface conditions are typically the cumulative product of multiple wave trains originating over a wide geographic area. As an example, an SS3 condition

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* W.J. Pierson, Jr., "Visual Wave Observations", Dept. of Meteorology and Oceanography, New York University, SP-44, March 1956.

may have components from a wave generated by a wave with a 50-mile fetch from a northeast direction, swells produced by a storm 300 miles to the east, and small wavelets from a local westerly breeze. This condition is illustrated in Figure 3-4.

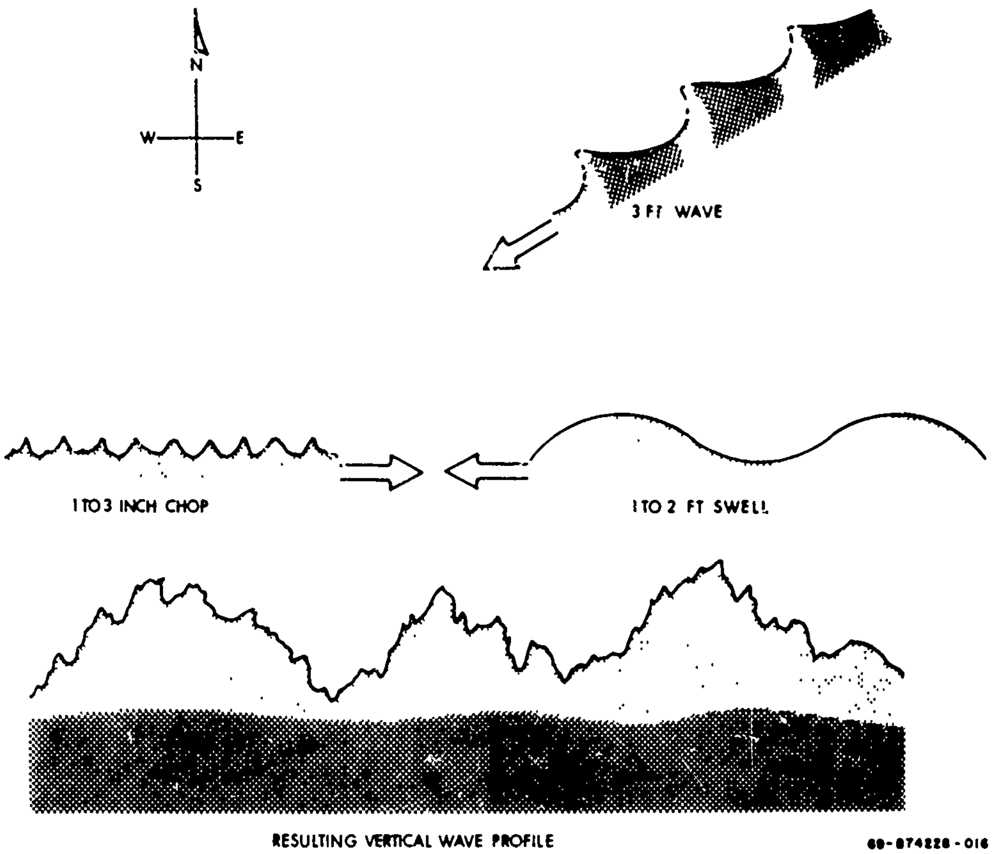

Figure 3-4. Wave Components

The vertical accelerometer output under similar sea conditions closely resembles* the hypothetical wave profile of Figure 3-4.

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* The accelerometer output will be displaced since maximum output will occur on the wave slope where the greatest change in acceleration takes place.

The continuous variation of the accelerometer was recorded. A correction can be applied to account for the effect of buoy tilt on the accelerometer. The inclinometer and accelerometer voltages are correlated with received signal strength variation to determine the effect of sea conditions.

3.2.2 PROCESSING

Ideally, one would like to work with a relatively smooth periodic wave profile in making an analysis. Two approaches were considered: (1) successive samples of the voltage waveform could be averaged with adjoining sets of values to produce a regular contour or, (2) the samples accepted as recorded and the data handled statistically. A combination of the two approaches was used. Because of the many data points, it was necessary to average every five points. These averaged points were plotted to determine signal characteristics.

All data was converted from analog to digital data at a rate of 100 data samples per second. Individual sample values were plotted against signal strength to produce scatter diagrams. Regression analysis was used to determine the best fit of curves to the sample point displacement on these diagrams.

3.2.3 DATA SOURCES

Data used in the analysis was derived from four sources. Many of the buoy transmissions were recorded on magnetic tape and with a two-channel pen recorder. Metered outputs and written comentary were additional sources of data used for the overall analysis.

3.3 SUMMARY OF MEASUREMENTS

The principle quantity measured was the received signal level and its range. Supporting this measurement were data on accelerometer variation, inclinometer position, temperature, humidity, pressure, and visual observations of sea conditions. Loss of signal due to wave washover was not observed during the measurements.

The wave surface is typically rippled and has multiple components. As a result there was no clearly identifiable accelerometer and inclinometer voltage output variation which can be interpreted as a particular class of wave condition. These measured values were treated statistically to determine if buoy tilt and buoy position on the wave was a factor in the strength of the received signal level.

Temperature, humidity, and pressure readings were used to determine the refractive index (N) existing at the time of measurement. A nomograph for this calculation is included in Appendix A. The refractive index was monitored to ensure that no unusual atmosphere conditions contributed to the received signal level.

The buoy antenna voltage standing-wave ratio (VSWR) was measured at each frequency for both a vertical and a 45-degree tilt position. This measurement indicates the expected transmitter load variation due to antenna aspect.

These measurements are summarized in the following three paragraphs.

3.3.1 MEASURED SIGNAL STRENGTH

A tabulation of recorded signal strengths is given in Tables 3-1 and 3-2. The time indicates when a sequence of buoy interrogations occurred. If all subsequent received data on that date was similar, no new entry was recorded. Information on low and high tide is included since the resulting change in sea level was approximately eight feet. This is equivalent to a corresponding change in the height of the receiving antennas.

The value of refractive index N is also tabulated. Since the value of N ranges between 300 and 321, no different refractive line-of-sight conditions other than the normal 4/3 earth radius are expected.

The range of measured signal levels was larger than expected. These levels have been plotted on Figure 3-5. During the measurements, the receivers were calibrated with a signal generator. This verifies that the larger signal strength measurements were valid.

The plots of Figures 3-6, 3-7, and 3-8 illustrate the rate of signal variation. (One-second time ticks are marked along the lower edge.) A relationship between signal variation and wave period seems to be indicated.

TABLE 3-1

SUMMARY OF COMPUTER RUNS

REF. NO.	DATE (1969)	TIME	TYPE	CONDITION	TILT	WIND	POWER IN μV	POWER XMIT	HIGH TIDE	LOW TIDE	N
H1	1-20	6:40pm	HF Roof	1 ft Sea			251	13W	12:42pm	7:00pm	321
H2	1-22	4:39pm	HF Shore	Calm			223-251		2:24pm	8:36pm	315
H3	1-25	3:20pm	HF Roof	4 ft Swell		SE 9 kts	251-281		5:06pm	10:52am 11:06pm	319
H4	1-20	6:58pm	HF Shore	1 ft Sea			251	13W	12:42pm	7:00pm	321
H5	1-27	4:20pm	HF Roof	2 ft Wave NW 1-2 ft Swell SE	Inclino-meter bad irregular	15 kts NW	130-158	10W	7:00pm	12:00am	300
H6	1-27	5:23pm	HF Roof	1-2 ft Swell SE	"	"	"	"	7:00pm	12:00am	300
H7	3-18	3:27pm	HF Shore	1 ft Sea		2-3 kts	6-15NV		11:18am	5:24pm	320
H8	3-18	3:58pm	HF Roof	1 ft Sea	6-31°	2-3 kts	30-50	13W	11:18pm	5:24pm	(320)
H9	3-19	2:45pm	HF Shore	6-10 ft Sea	4-39°	26-35 kts	6-12	13W	12:00pm	6:06pm	318
H10	3-19	3:36pm	HF Roof	6-10 ft Sea	29-36°	"	30-50	13W	12:00pm	6:06pm	318
H11	3-27	4:09pm	HF Roof	2 ft Sea		2 kts	125-175	10W	6:36pm	12:24pm	300
H12	3-27	4:28pm	HF Shore	2 ft Sea	27-31°	20 kts	7-15NV	10W	6:36pm	12:24pm	300
V1	1-7	1:44pm	VHF	Sea State 3		2-9 kts	10-80NV	5W	1:30pm	7:48pm	308
V2	1-8	15:13pm	VHF	Sea State 1		W 10 kts	2-10NV	5W	2:12pm	8:30pm	306
V3	1-29	1:48pm	VHF	3 ft Swell E 1 ft Waves N	34-47°	10 kts NW	50-80	7W	8:06am	2:36pm	320
V4	3-6	5:06pm	VHF	2 ft Wave	6-49°	9 kts W	30-80	7W	12:42pm	6:48pm	300
V5	4-2	3:31pm	VHF	2 ft Wave		7-9 kts SW	4-7NV	7W	10:48am	5:00pm	320
V6	4-3	12:52pm	VHF			7-9 kts NW	3. 10-10NV	7W	11:30am	5:42pm	312
V7	4-4	10:15pm	VHF			3-6 kts	4-8NV	5W	12:18pm	6:06am	316
U1	3-6	6:09pm	UHF	1 ft Wave	12-40°	9 kts W	1-1.5	4W	12:42pm	6:48pm	300
U2	3-7	2:16pm	UHF	3-4 ft Sea	28-45°	7-9 kts NNE	0.5-1	4W	1:24pm	7:30pm	302
U3	3-17	8:10pm	UHF	1 ft Sea		9 kts SE	0.5-1	4W	10:54pm	4:42pm	-
U4	3-18	3:45pm	UHF	1 ft Sea	21-35°	2-3 kts NNE	0.4	4W	11:18pm	5:24pm	(320)

TABLE 3-2

SUMMARY OF GRAPHIC RECORDINGS AND MONITORED DATA

REF. NO.	DATE	TIME	TYPE	CONDITION	TILT	WIND	POWER IN μV	TIDE	N
V8	12/20/68	12:34pm	VHF	6-inch wave motion slight swells - wind gusts to N 4-6 kts - Fog/Snow	-	-	20	-	314
V9	12/20/68	2:38pm	VHF	Sea 1-ft waves - Fog - Medium to light snow	Buoy tipping up to 45°	-	35	-	314
H12A	1/7/69	10:55am	HF ROOF	Estimated low side SS-3 - Reference 10-12 ft swells sensors indicated rough conditions - wind 4-7 kts	-	2-9 kts	80 avg. down to 10	L 7:18 am H 1:30 pm	320
H13	1/7/69	1:24pm	HF SHORE	Off-Shore 4-6 ft 3-5 sec period - estimate SS-3 - wind 3-5 kts	-	2-9 kts	100-150	L 7:18 am H 1:30 pm	311
H14	1/16/69	2:12pm	HF ROOF	4-5 ft swells - 1-ft waves with white caps	-	5-9 kts E	178	L 3:30 pm H 9:00 am	303
H15	1/16/69	4:11pm	HF SHORE	" "	-	5-9 kts E	178	"	303
H16	1/17/69		HF SHORE	2-3 ft swells - white caps wind W - gusts to 8 kts	-	3-5 kts W	178	H 10:00 am L 4:30 pm	303
H17	1/17/69	3:13pm	HF ROOF	" "	-	3-5 kts W	178	H 10:00 am L 4:30 pm	303
H18	1/22/69	5:00pm	HF ROOF	Calm	-	-	195-223	L 8:36 pm H 2:24 pm	315
H19	1/20/69	7:09pm	HF SHORE	1-ft Sea	-	-	251	L 7:00 pm H 12:42 pm	321
V10	3/17/69	8:18pm	VHF	1-ft Swell	-	9 kts SE	30-50	L 4:42 pm H 10:54 pm	-
H20	3/19/69	4:26pm	HF SHORE	6-10 ft Seas	29-36°	-	12	L 6:06 pm H 12:01 pm	318
H21	3/28/69	5:45pm	HF ROOF	2-ft Sea	-	17 kts SSE	45	L 1:18 pm H 7:30 pm	307
H22	3/28/69	6:02pm	HF SHORE	2-ft Sea	-	17 kts SSE	6	L 1:18 pm H 7:30 pm	307
U5	4/2/69	5:04pm	UHF	2-ft Sea	-	7-9 kts SW	0.5	L 5:00 pm H 10:48 am	320
V11	4/5/69	4:55pm	VHF	-	-	-	6-10	L 1:36 pm H 7:06 pm	306
U6	3/27/69	4:58pm	UHF	2-ft Wave	-	17 kts W	<5	L 12:24 pm H 6:36 pm	300

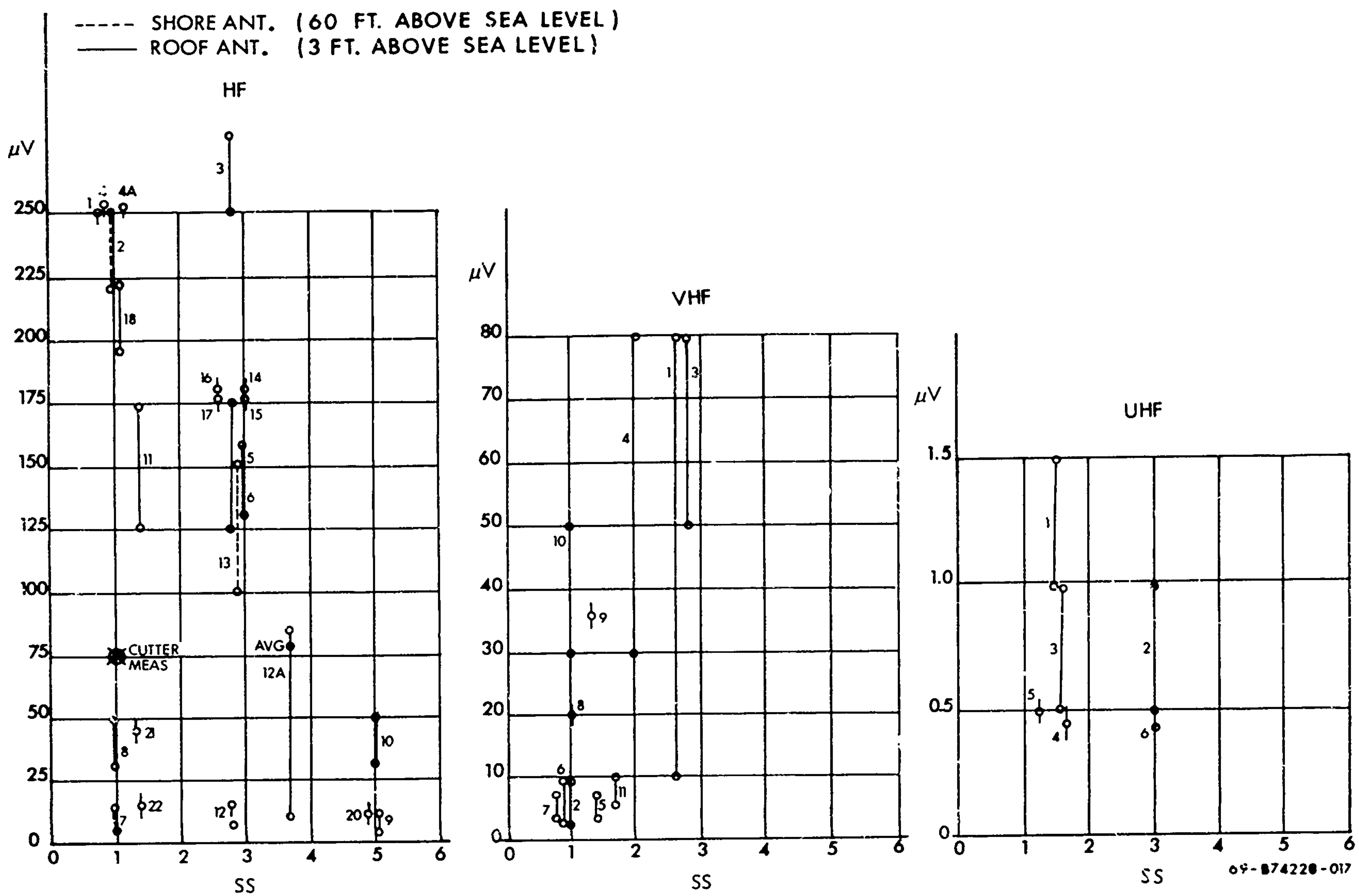

Figure 3-5. Received Signal Levels

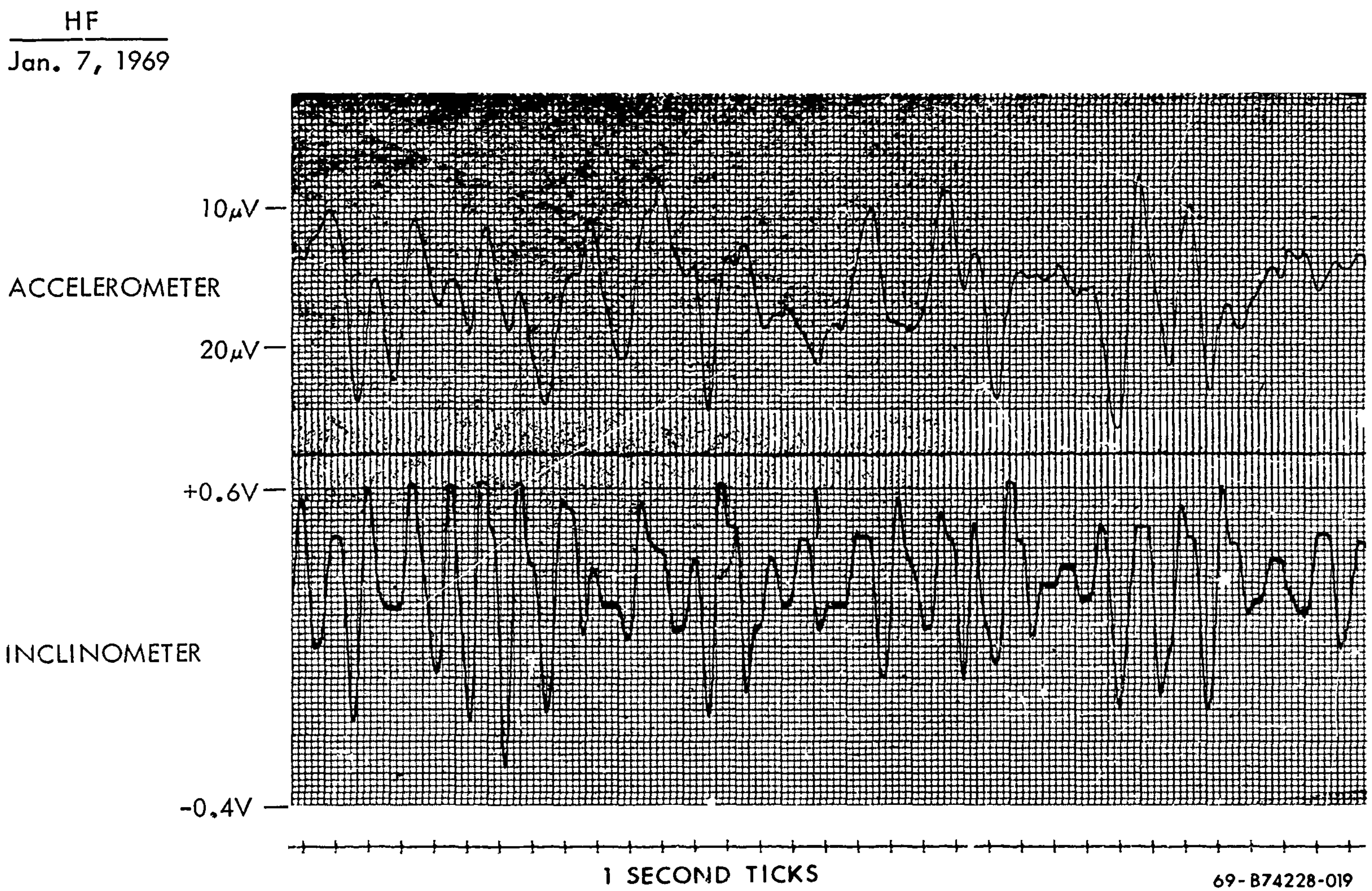

Figure 3-6. Signal Variation Recording

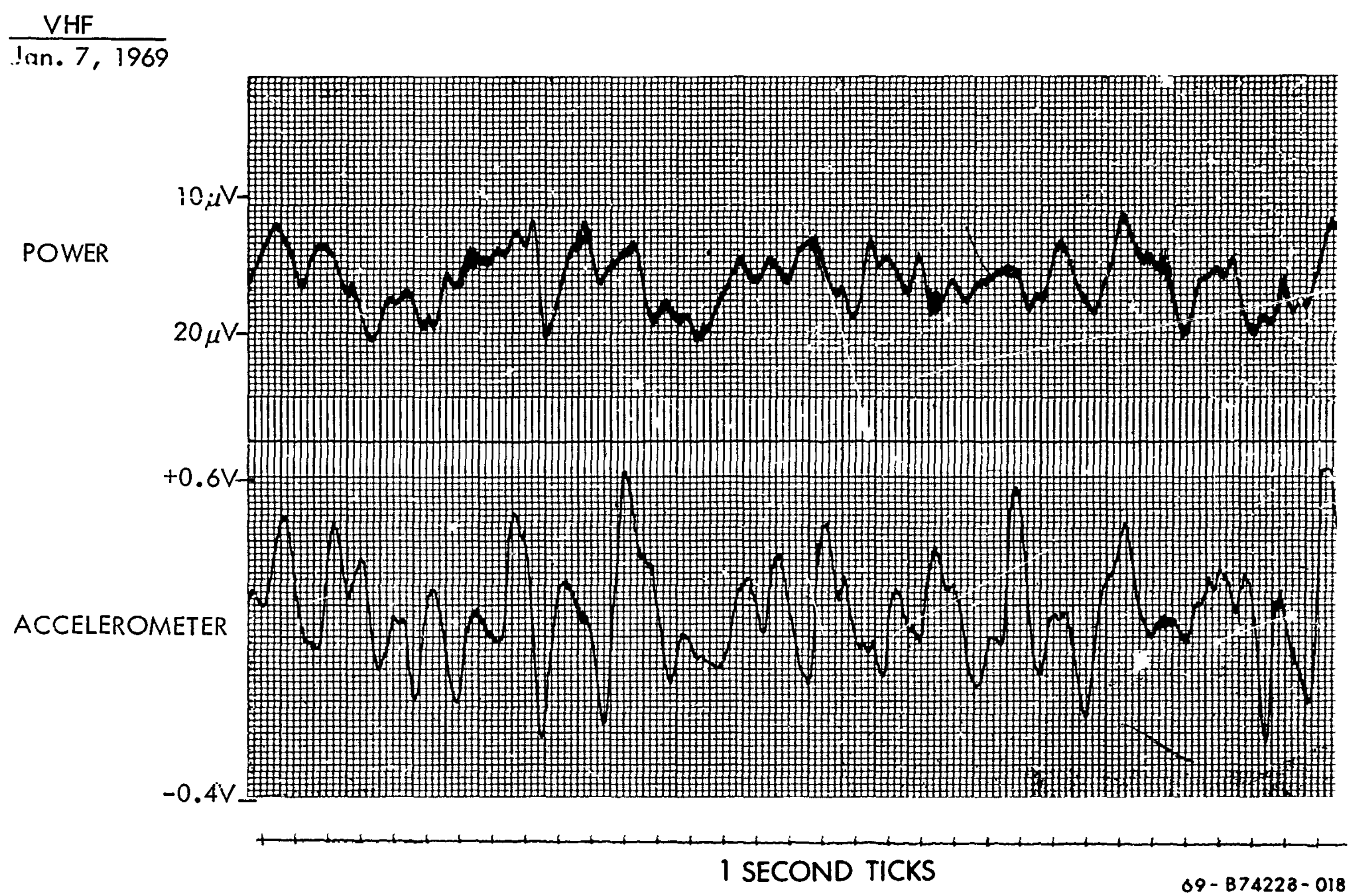

Figure 3-7. Signal Variation Reading

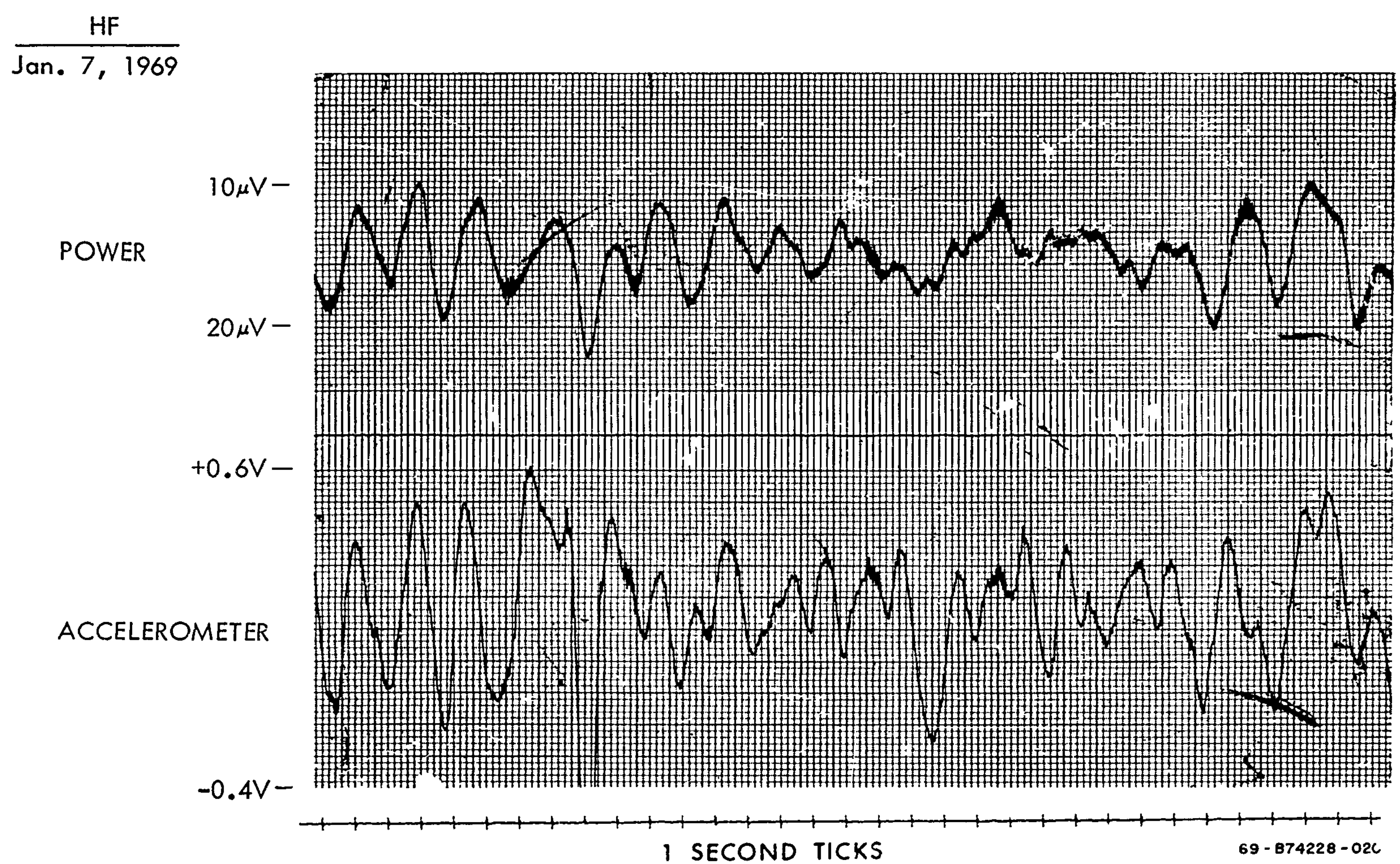

Figure 3-8. Signal Variation Recording

3.3.2 MEASURED AMBIENT CONDITIONS

These measurements include buoy attitude and atmospheric conditions which provide a reference for correlating signal strength variations to ambient conditions. Analysis of each of these measurements will contribute to an overall understanding of propagation variables.

3.3.2.1 Tilt

Buoy tilt was determined by the voltage output of two 90-degree oriented inclinometers within the buoy. The received signal levels from these inclinometers were converted to equivalent degrees-of-tilt in each direction. These angles were then used to calculate the actual buoy tilt. All measured values were converted from analog to digital data at a rate of 100 data-samples per second. The computer listing tabulated the original inclinometer measurements and the resulting calculated angle. Degrees of buoy tilt versus signal strength have been plotted. The resulting graph is a scatter diagram and provides a means of recognizing relationships between two variables. Figures 3-9, 3-10, 3-11, and 3-12 show scatter diagrams relating signal strength and buoy tilt. The majority of the plots show no relationship between buoy tilt and signal strength. The one exception is Figure 3-10 which shows higher signal levels at larger tilts. One explanation for this might be the effect of the buoy structure on the indirect signal return.

It is concluded that the tipping of the buoy antenna due to buoy tilt is not a significant factor in received signal strength for broad vertical beam antennas. Similar conclusions have been indicated in other investigation references.[(1)] [(2)]

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(1) "A Study of Transmission of Weather and Oceanographic Data from Floating Weather Stations", Report SRA-416, Smyth Research Associates, p. 22, Oct. 1964.

(2) "Whip Antenna Tilting Effects", J. Keegan, Sanders Associates, JK-65-4052, Feb. 1965.

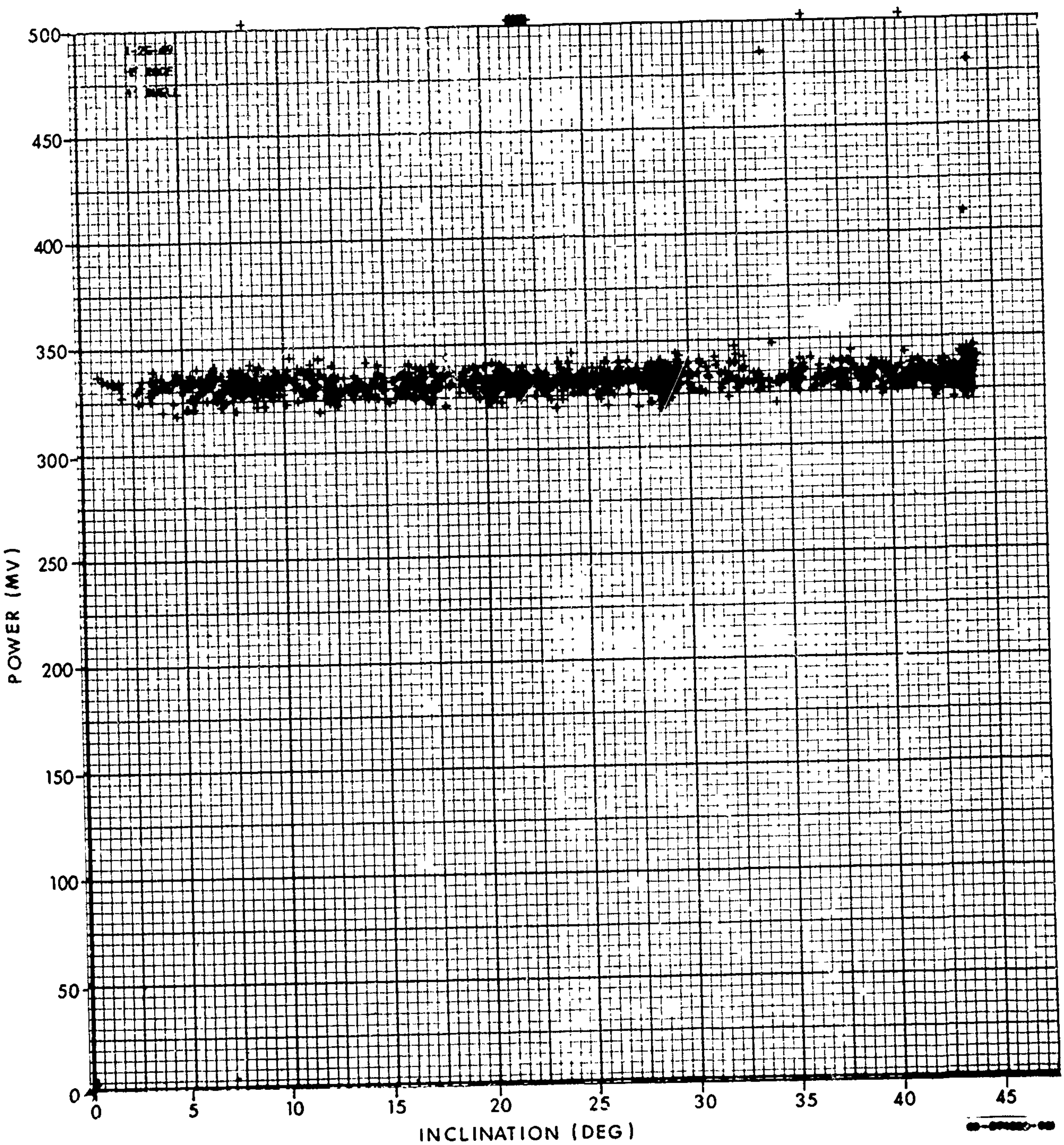

Figure 3-9. Scatter Diagram

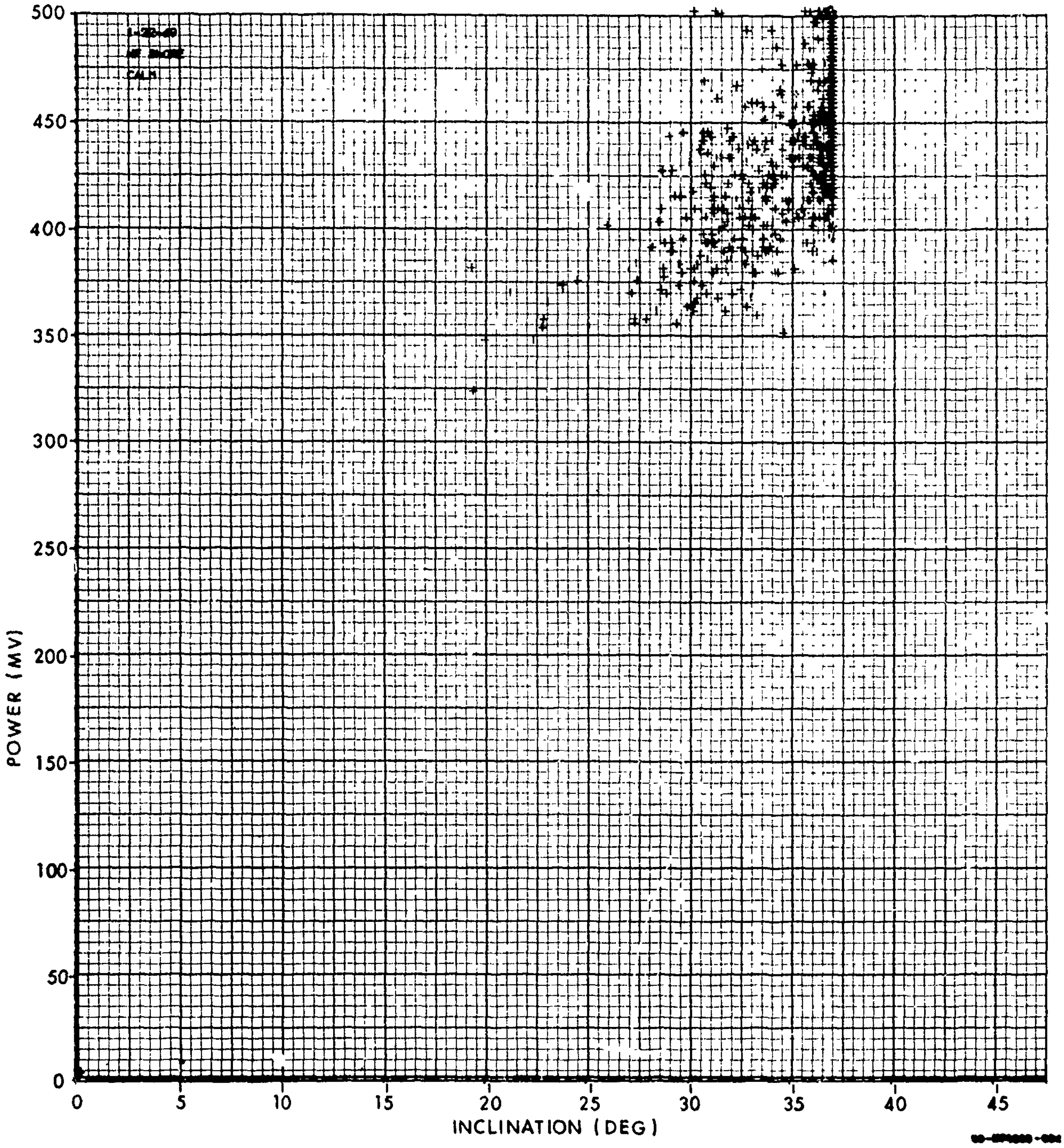

Figure 3-10. Scatter Diagram

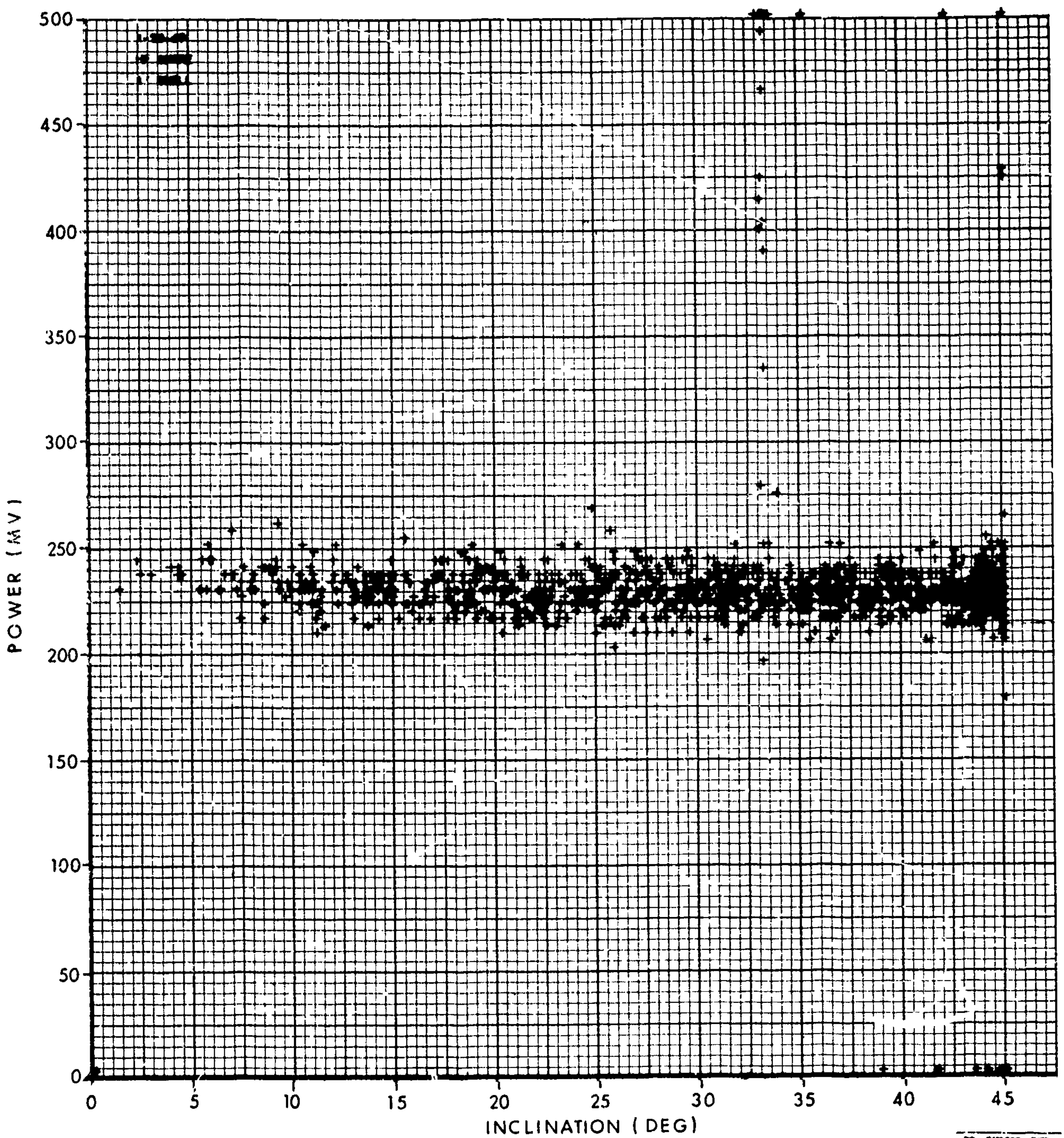

Figure 3-11. Scatter Diagram

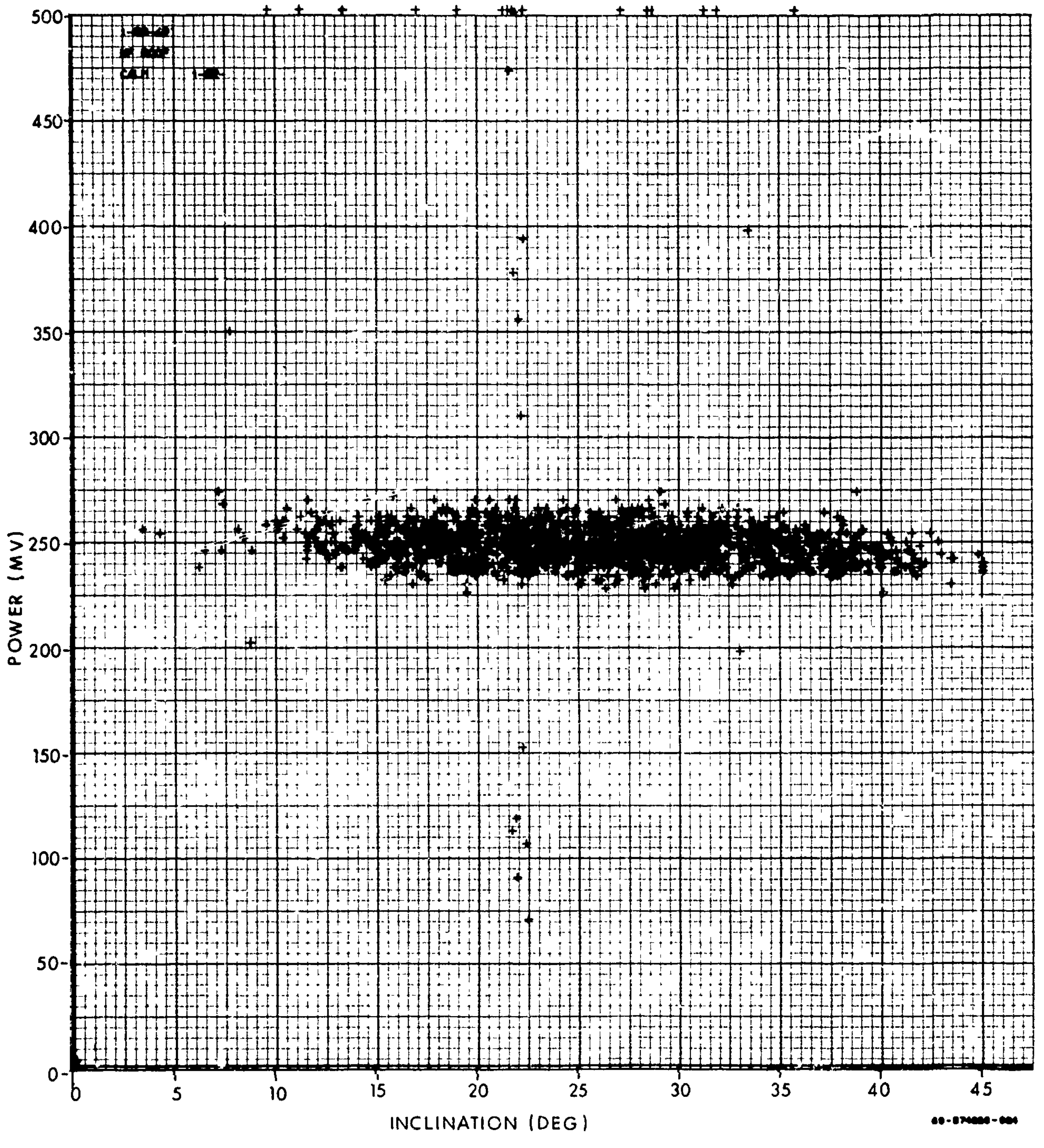

Figure 3-12. Scatter Diagram

3.3.2.2 Accelerometer

A scatter diagram of signal level and accelerometer output voltage is shown in Figure 3-13. This diagram indicates no relationship between an accelerometer voltage equivalent to wave crest or thoughs, and maximum and minimum power points. Even taking into consideration a voltage bias due to accelerometer tilt, there is no apparent offset pattern indicating such a received signal/wave correlation. The data of the diagram of Figure 3-13 is for a buoy transmitting at VHF frequencies. At HF, the surface disturbance due to waves is a much smaller percentage of a wavelength and consequently will have a smaller effect.

Although the scatter diagram does not show any wave-crest/maximum signal and wave-trough/minimum signal correlation, inspection of plots of signal level and accelerometer output (Figures 3-7 and 3-8) does show a similar pattern. This is supported by the scatter diagram which indicates a relationship between positive accelerometer voltages* and maximum signal levels, and negative accelerometer voltages and minimum signal levels. A plot showing the correlation between the signal strength waveform and accelerometer voltage waveform (Figure 3-6) is shown in Figure 3-14. Further processing of the accelerometer voltage to determine buoy displacement and then making a comparison with signal level did not indicate a maximum signal-to-wave crest relationship. This supports the previous observation. Although no definite conclusions can be made based on this data, it does suggest that the buoy position relative to the wave face is significant. One explanation may be that the indirect wave component of the signal is reduced either by the proximity or the roughness of an ascending wave slope. Further insight may be gained through a recent analysis by D. Barrick** which considered surface roughness and the effective surface impedance.

* Positive accelerometer voltages indicate an upward acceleration while negative voltages indicate downward motion.

** "HF/VHF Surface-Wave Propagation Across a Rough Sea", Paper by D. Barrick at URSI meeting April 23, 1969 at Washington, D.C.

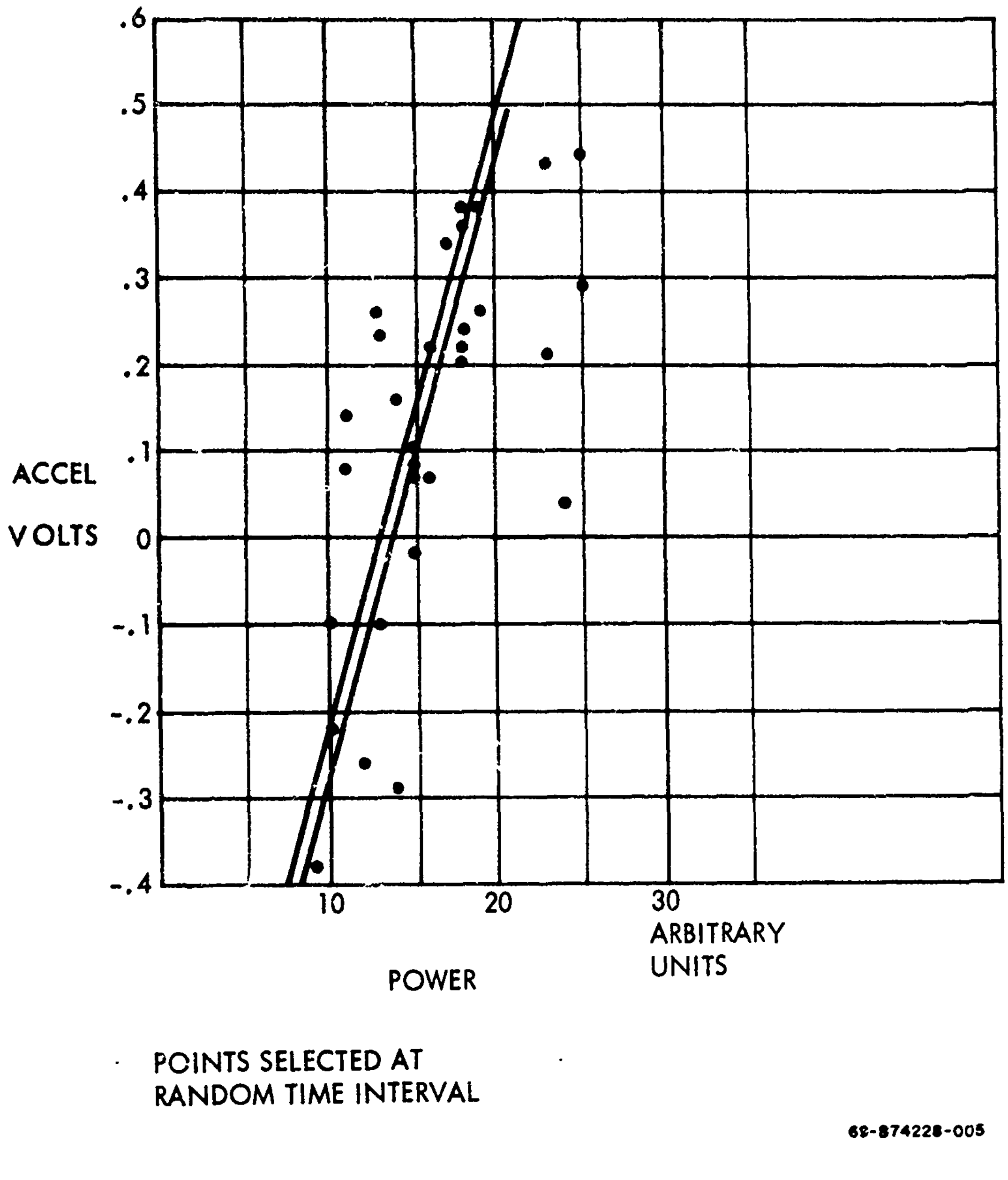

Figure 3-13. Scatter Diagram

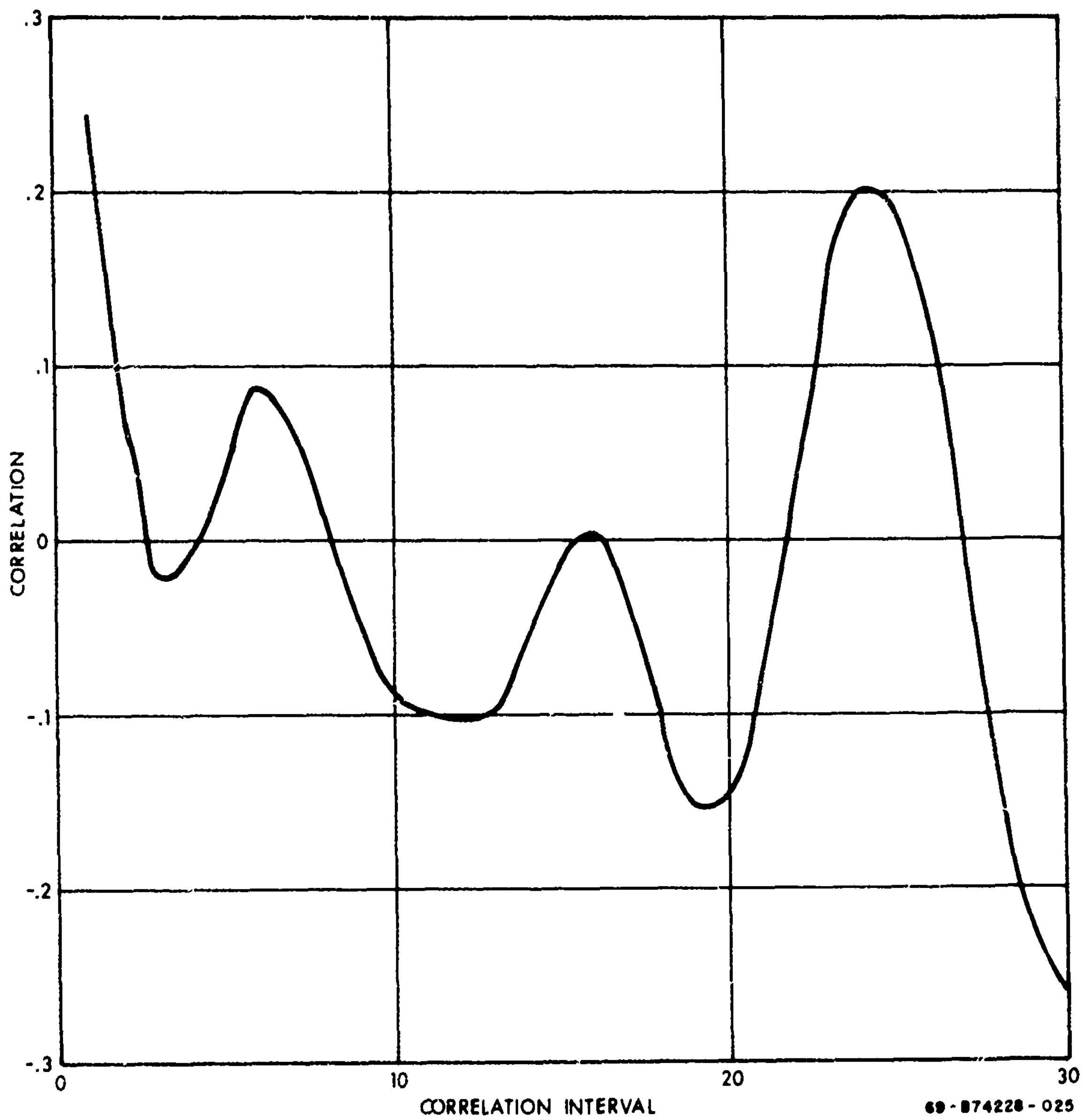

Figure 3-14. Correlation Interval

3.3.2.3 Physical Constraints

The calculation of buoy tilt shows that during many of the measurements the average tilt of the buoy was 20 to 30 degrees. This tilt was due to the mooring cable. While the resulting tilt does not cause a large change in antenna pattern or radiated signal level, the mooring cable appeared to dampen buoy movement. This restricted the ability of the buoy to follow wave motion and, while the effect on the measurements is not apparent, better following action would have been desirable.

Icing conditions were prevalent during January tests. Layers of ice up to 4-inches thick formed on the top plate of the buoys. The antenna remained free from ice because of their flexible design. There were no indications that the measurements were affected by the ice.

3.3.2.4 Refractive Index

The refractive index provides a measure of radio-wave bending by the atmosphere. The extent of this bending determines the line-of-sight range and is a factor in the determination of transmission path propagation loss. The refractive index, N, is defined as:

$$N = \frac{77.6}{T} \left(p + 4810 \frac{e}{T}\right)$$

where T = temperature

p = pressure

e = vapor pressure

A more detailed discussion is given by reference (3). Throughout the measurements, pressure, temperature, and humidity were recorded so that the refractive index could be monitored. Of principle interest was the possibility of large values of N which are comparable to large equivalent earth radius conditions (k) or abnormal long line-of-sight propagation conditions. Rapid changes in the value

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(3) E. Gossard, "Radio Refraction by the Marine Layer and its Effect on Microwave Propagation"

of N as a function of altitude are associated with ducting conditions. Ducting was not considered a serious factor at the frequencies used during the tests.

The relationship of N values and the equivalent earth's radius factor (k) is given in Table 3-3.

TABLE 3-3

RELATIONSHIP OF (N) AND (k)

N	k
200	1.17
250	1.23
301	1.33
313	1.36
350	1.49
400	1.77

A field strength curve[4] for different values of k at 300 MHz is given in Figure 3-15.

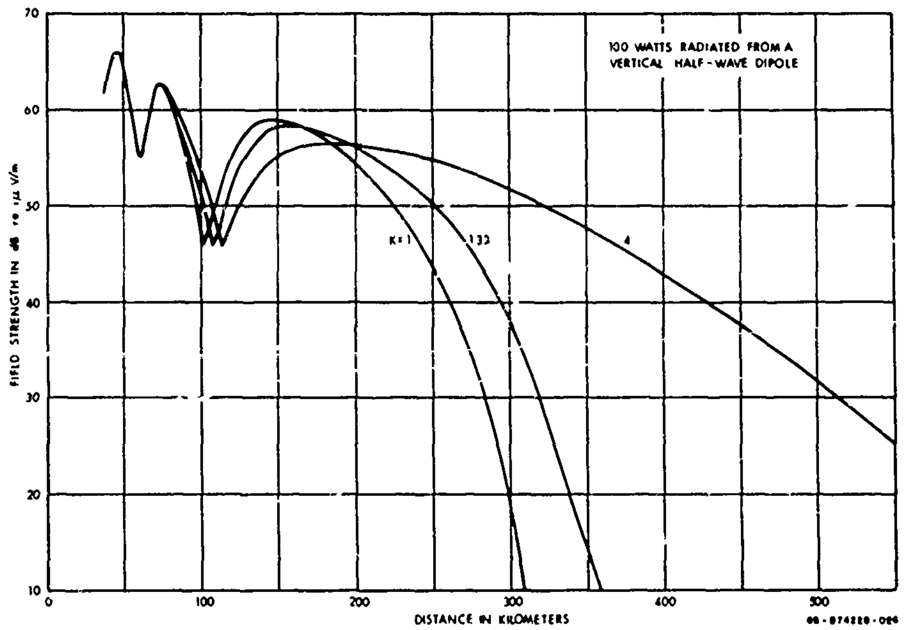

Figure 3-15. Theoretical Field Strength Curves

(4) Ince and Williams, "Long Range Ground-to-Air Communications", IEEE Transactions on Comm. Tech. Oct. 1967

Although the curve is not for the same measurement conditions, it does show how large k must be to affect field strength. During the buoy measurements, the values of N ranged from 300 to 321. The equivalent values for k are small atmospheric conditions and were not serious factors in the signal strength measurements.

3.3.2.5 Antenna VSWR

In order to determine if changes in transmitter loading was occurring due to buoy tilting, the voltage standing-wave ratio (VSWR) of the buoy antennas was measured. High VSWR is indicative of a bad mismatch and would result in a decrease in the output power of the transmitters.

The VSWR of the buoy antennas were measured in the vertical and 45-degree tilt positions of the antennas. The VSWR of the antennas at HF and VHF showed little change while the UHF antenna VSWR improved from 3.2 to 2.4 at 45-degree tilt. While the load change may produce small variations in output power, the effect was not considered critical to the program objective and the transmitters were not calibrated for this effect. Furthermore, detailed results of the change in antenna impedance is given in a report by E. Stevens[5] (et. al). Their results showed the antenna impedance to be relatively constant under tilt angles expected in normal operation.

(5) E. Stevens, G. Poaps, G. Moss, "Impedance Measurements of Sonobuoy Antennas in Their Operation Environment," DRTE Technical Note #614, Defense Research Board, Dept. of National Defense, Canada, Feb. 1969

SECTION 4
TEST DATA APPLICATION

4.1 GENERAL

At this point it is pertinent to restate the objective of this program. The objective is the determination of the effects of sea conditions on buoy communications. More specifically, we are concerned with the most critical situation of low-angle or over-horizon propagation over sea water. The result to be achieved is to determine what power margin must be added to buoy communication system designs to ensure reliable communications under rough sea conditions

The test data has been summarized in the preceding sections. This section will first discuss the nature of propagation over water, describe computer prediction methods and previous measurements results. Then in Paragraph 4.5, all of these inputs will be used to provide a comprehensive approach to propagation design under the conditions described.

4.2 NATURE OF PROPAGATION

Solutions to the problems of radio propagation has been the objective of workers in this field since about 1909. Among the earliest works was an analysis by Sommerfeld* who solved the general problem of radiation from a vertical

* A. Sommerfeld "The Propagation of Waves in Wireless Telegraphy" Ann. Physik, 28, 665 (1909)

antenna over a plane earth having finite conductivity. Of more recent vintage are the papers by Norton* in which he reduced the Sommerfeld theory to equations which allow an engineering solution to propagation problems. These equations distinguished between a space and surface-mode of propagation. The elementary geometry is shown in Figure 4-1.

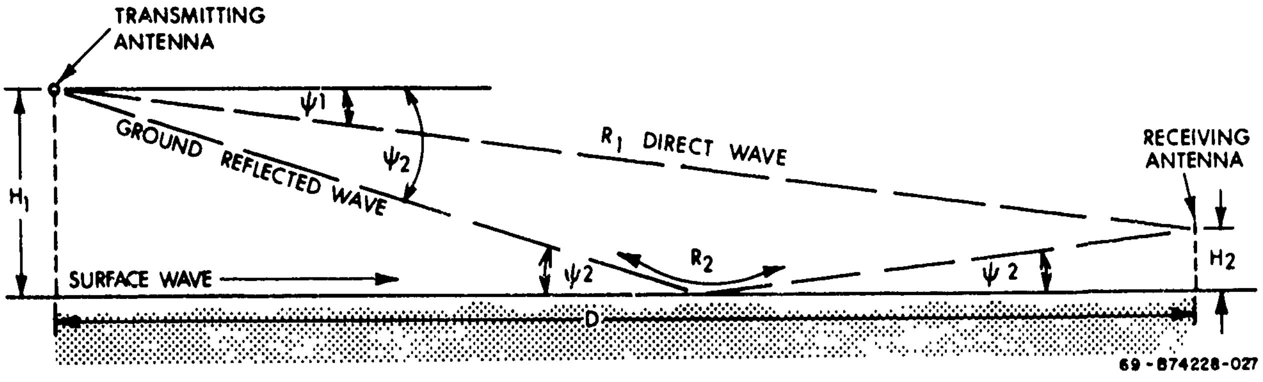

Figure 4-1. Plane Earth Propagation Geometry

The equations developed by Norton** are applicable at large distances from the antenna since the higher order $1/R_1$ and $1/R_2$ terms have been neglected. Separating these equations into a space and surface wave component:

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* K.A. Norton, "The Propagation of Radio Waves Over The Surface of the Earth and In The Upper Atmosphere", Proc. IRE, 24, 1367 (1936); Proc. IRE, 25, 1203 (1937); Proc., IRE, 25 1192 (1937)

** A good introductory discussion of these equations is given in E. Jordan, "Electromagnetic Waves and Radiating Systems", Prentice-Hall, Inc., 1950.

$$E_{total\ space} = \sqrt{E_z^2\ (space) + E_s^2\ (space)}$$

$$= \underbrace{\underbrace{j\ 30\ BI\ dl\ (\cos\psi)\ \frac{e^{-jBR_1}}{R_1}}_{\text{direct wave}} + \underbrace{j\ 30\ BI\ dl\ (\cos\psi) R_v\ \frac{e^{-jBR_2}}{R_2}}_{\text{ground reflected wave}}}_{\text{space wave}}$$

$$E_{total\ surface} = j\ 30BI\ dl\ (1-R_v)\ F\ \frac{e^{-jBR_2}}{R_2} \left[1-2u^2 + (\cos^2\psi)u^2\ (1+\sin^2 \frac{\psi}{2})\right]^{1/2}$$

This form of the equation provides a physical insight into the nature of propagation. Each expression contains a $\frac{e^{-jBR_n}}{R_n}$ term which represents a spherical wave radiating from the antenna. The e^{jBR_n} accounts for the phase of the received signal and the $1/R_n$ term results in a decrease in field intensity as an inverse function of distance. All three terms are a function of the angle ψ of signal propagation. The reflected-wave and surface-wave expressions includes an R_v term which is the reflection coefficient and phase. The parameter will directly effect the antenna radiation pattern.

The equations presented illustrate that three separate transmission components must be considered. The direct wave is dominant at line-of-sight distances and the reflected wave causes reinforcement or cancellation of the direct wave. This accounts for antenna pattern lobing effects which occur particularly over water*. The surface wave becomes important at over-horizon distances.

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* Reed and Russell, "Ultra High Frequency Propagation", Boston Technical Publishers, 1964.

Of particular interest is the expected antenna-gain reduction which will occur at low angles. Ordinarily, the pattern for a vertical monopole antenna located on a ground plane of infinite conductivity is considered a single lobe with essentially constant gain to an angle 20 to 30 degrees above the surface. This will not be the case and the effect of a finite surface conductivity is discussed in the following paragraph.

4.2.1 ANTENNA PERFORMANCE OVER SEA WATER

The finite conductivity of the sea surface will change the antenna radiation characteristics. The principle effect is a change in the vertical radiation pattern which results in a decrease in the received signal strength at low-horizon angles. This is caused by the cancellation effect of the indirect wave on the direct wave at low angles. Typically, the vertical antenna pattern for a quarter-wave antenna located on an infinite conductivity plane is illustrated in Figure 4-2.

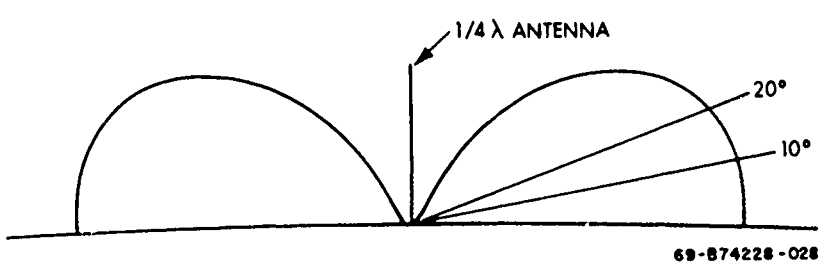

Figure 4-2. Vertical Pattern-Infinite Conductivity

When the plane has finite conductivity as in the case of the sea surface, the antenna radiated field pattern is reduced at low angles and with a consequent reduction of gain. This is illustrated in Figure 4-3. This change may also be considered

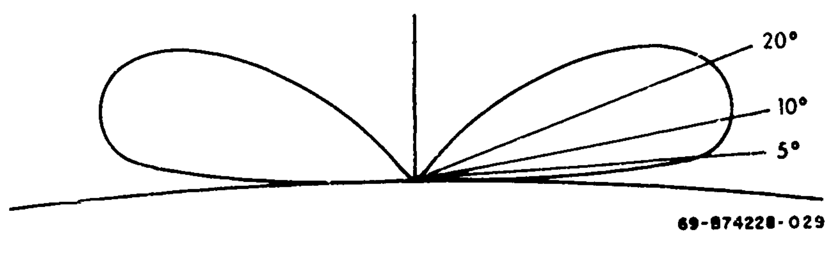

Figure 4-3. Vertical Pattern-Finite Conductivity

from the standpoint of Fresnel zone clearance*. For an antenna located on the sea surface, low-angle line-of-sight transmission will produce a situation where the energy in the first Fresnel zone of the radiated signal will intercept the sea surface. This results in an increase in transmission loss that is proportional to the degree of Fresnel zone interception. An example of the interception geometry is shown in Figure 4-4.

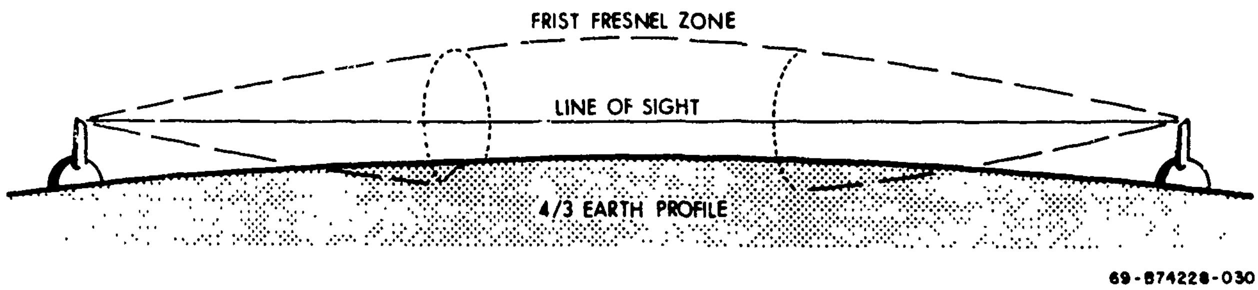

Figure 4-4. Fresnel Zone Geometry

If the line-of-sight path clearance is less than 0.6 the radius of the first Fresnel zone, the transmission will not be free space and a loss factor must be included for low angle radiation.

4.2.2 CHANGES IN RECEIVED SIGNAL LEVEL

Signal strength variation at the receiver can be due to the following four factors:

- Buoy tilt producing a change in antenna VSWR. This is equivalent to an antenna impedance change which could reduce the power output from the final output amplifier of the buoy transmitter.

- Buoy tilt producing a shift in the antenna gain in the direction of the receiver. This effect would be equivalent to operating along a different radial direction of the antenna gain pattern. When the antenna is physically located a wavelength or more above the surface, a lobing pattern would be expected and a more pronounced change to the pattern nulls is expected.

* The first Fresnel zone is the distance from any spot on the ground from which a reflected indirect wave will travel a half wavelength longer than a direct wave.

- Diffraction of the radiated signal by sea wave interception.
- Change in the impedance* of the ocean surface with a resulting change in the surface path attenuation and reflection coefficient.

The buoys used during the test had antennas located close to the ocean surface. Physically, they resemble the buoy types used for the VSWR measurements in the Defense Research Board report**. Since this report shows only a small change in VSWR for tilt angles up to 45 degrees, for a buoy with an antenna ground plane the power delivered to the buoy antennas will be considered constant.

Characteristically, the vertical gain pattern of a monopole antenna is essentially constant over angles to about 45 to 60 degrees above the horizon. Therefore, antenna gain is considered constant for the range of tilt angles encountered during the test.

There remains only the last two factors to be investigated as the effects producing variation of the received signal strength.

4.3 COMPUTER PREDICTION

Two computer programs have been investigated as prediction methods. Both programs have been developed by the Environmental Science Service Administration (ESSA), Boulder, Colorado. The first is called GROUNDWAVE and was designed by L. Berry and M. Chrisman of ESSA. This computer program treats smooth-earth propagation and provides a prediction of field strength, as a function of range relative to a reference antenna/transmitter source. The second program was designed by P. Rice and A. Longley of ESSA and is called COMTE. This program allows irregular terrain features to be included in the computation and outputs a prediction of dB of propagation loss below free space loss, as a function of range. Both of these programs have been compared against measured results to determine the relative utility of each.

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* This effect has been considered by D. Barrick in his paper, op, cit.

** op. cit. G. Stevens, et al

4.3.1 PREDICTED FIELD STRENGTH USING GROUNDWAVE* PROGRAM

The program was run for ranges out to 320 km, using a conductivity factor of 5 and a dielectric constant of 80.

The computer printout gave predicted field strengths over a range of 10 to 100 km in 3-km increments and out to 320 km in 20-km increments. The value of E on the printout is given referenced to a unity dipole current moment. This value must be multiplied by an equivalent dipole current moment to compensate for the actual radiated power from each buoy. Computer printouts for frequencies of 30.14 MHz (roof antenna), 30.14 MHz (shore antenna), 173.5 MHz, and 406.5 MHz respectively are provided in Appendix D.

The predicted field strength at 12 km is determined by interpolating between the 10- and 13-km values. The equivalent dipole current moments have been calculated** using field strengths measured at a one mile reference point and by means of a radiated power expression.*** The equivalent dipole current moments are:

		Equivalent dipole current moment	
		1-mile ref.	radiated pwr.
30.14 MHz (roof antenna)	-	0.0228	0.940
30.14 MHz (shore antenna)	-	0.0120	0.940
173.5 MHz	-	0.0108	0.306
406.5 MHz	-	0.0037	0.0982

The "1-mile reference" values are considerably lower. Even allowing for measurement errors in obtaining the 1-mile signal strength and calculation of antenna aperature, a large difference still exists. The relative prediction results will be discussed in Section 4.5.

* Program developed by Leslie A. Berry and Mary E. Chrisman, ESSA (formerly National Bureau of Standards) Report 9178

** Appendix B

*** Appendix C

Interpolating the values given in the computer printout:

PREDICTED FIELD STRENGTH

AT 12 km (6.5 nmi)

(Unity Dipole Current Moment)

FREQUENCY	ANTENNA	VOLT/METER
30.14 MHz	Roof	1.34×10^{-3}
30.14 MHz	Shore	1.78×10^{-3}
173.5 MHz	-	6.45×10^{-4}
406.5 MHz	-	10.02×10^{-4}

The predicted field strength is obtained using the expression:

$$\text{Predicted field strength} = (\text{Predicted field strength Unity dipole moment}) \times (\text{equivalent dipole moment})$$

Using both equivalent dipole current moments, the calculated values of field strength are shown below:

PREDICTED FIELD STRENGTH

AT 12 km (6.5 nmi)

FREQUENCY	ANTENNA	BUOY TRANSMITTER POWER	μVOLT/METER (1-mile ref)	μVOLT/METER (rad. power)
30.14 MHz	Roof	14W	30.6 μV/m	1260 μV/m
30.14 MHz	Shore	14W	21.5	1670
173.5 MHz	-	7W	7.0	198
406.5 MHz	-	4W	3.78	100

The value of signal strength was obtained using the antenna aperture/impedance factors calculated in Appendix B to convert the field strength in μV/m to the equivalent voltage in μV at the antenna terminal.

FREQUENCY	ANTENNA	FACTOR ANT. APER/ IMPED	LINE LOSS dB	RECEIVED SIGNAL (1 mile ref) µV	RECEIVED SIGNAL (rad signal) µV	DIFF dB
30.14 MHz	Roof	0.854	0.9	32.4	1330	32
30.14 MHz	Shore	0.721	4.0	18.8	1460	37.5
173.5 MHz	-	4.1	2.3	1.0	37.2	31
406.5 MHz	-	7.5	3.9	0.32	8.5	27.5

4.3.2 PREDICTED PROPAGATION LOSS USING COMTE PROGRAM

The COMTE* program was run for the same ranges and using the same constants as the GROUNDWAVE program.

The computer printouts were obtained for the propagation loss in decibels below the free space loss over a range of 10 to 100 km in 3-km increments and to 320 km in 20-km increments. Runs were made for average terrain irregularities of 0.5 and 4 meters.

The predicted field strength at 12 km (6.5 nmi) is determined by interpolating between the 10 and 13-km values. The 0.5 and 4-meter irregularity loss computations differ by a maximum of 1 dB for both 30.14 MHz and 173.5 MHz out to 40 km. The 406.5 MHz computation of loss for the two irregularities differs by about 3 dB at a range of 40 km. Because of the small difference in predicted loss only the 0.5 meter irregularity run will be used for field strength prediction.

Interpolating the value of added propagation loss and calculating the free loss, the combined propagation loss is given in Table 4-1.

The received signal level is computed assuming the following conditions:

Transmitter Power:	14 watts at 30.14 MHz	11.4 dBW
	7 watts at 173.5 MHz	8.4 dBW
	4 watts at 406.5 MHz	6 dBW

* Program developed by P. Rice and A. Longley, ESSA, Report ERL-79-ITS 67

Antenna Gain and Line Loss:	Transmitting Antenna	Line Loss	Receiving Antenna
at 30.14 MHz (roof)	-8 dB	0.9 dB	0 dB
at 30.14 MHz (shore)	-8 dB	4 dB	+3.0 dB
at 173.5 MHz	+0.5 dB	2.3 dB	+3.2 dB
at 406.5 MHz	+0.5 dB	3.9 dB	+7.5 dB

TABLE 4-1

TOTAL PROPAGATION LOSS

AT 12 km (6.5 nmi)

FREQUENCY	ANTENNA	IRREGULARITY LOSS	FREE SPACE LOSS	TOTAL LOSS
30.14 MHz	Roof	9.75 dB	83.7 dB	93.4 dB
30.14 MHz	Shore	9.82 dB	83.7 dB	93.5 dB
173.5 MHz	-	24.01 dB	98.9 dB	122.9 dB
406.5 MHz	-	27.73 dB	116.3 dB	144.0 dB

Summing the individual losses and gains at each frequency, the received signal level at the receiver is:

FREQUENCY	RECEIVED POWER	RECEIVED VOLTAGE
30.14 MHz (roof)	-97.8 dBW	193.0 μV
30.14 MHz (shore)	-97.3 dBW	193.0 μV
173.5 MHz	-118.1 dBW	17.6 μV
406.5 MHz	-140 dBW	1.4 μV

The value computed using COMTE is in good agreement with the measured values.

4.4 SUPPLEMENTAL MEASUREMENTS AND ANALYSIS

The data from two other measurement programs and an analysis using ray theory are related to this measurement program. This data will provide additional insight into over-water propagation effects.

The programs considered are the Project 499 measurements, the buoy-to-ship measurements made from the Coast Guard Cutter Decisive, and an analysis of signal diffraction by waves using ray theory.

4.4.1 PROJECT 499 MEASUREMENTS

The measurements taken during the Project 499 program* included low-angle propagation measurements from a buoy to an aircraft. The aircraft flew at a nominal 40,000-foot altitude out to ranges 120 nmi from the buoy. The buoy operated at UHF frequencies with an output power of 4.5 watts. At the extreme range the propagation angle was approximately four degrees. The angles of interest are lower (1-degree or less) for the measurements of this study; but, the Project 499 results do indicate a trend towards increased loss at low-angles. These results are indicated in Figure 4-5.

This graph shows that the average signal decreases to 8-9 dB below the predicted level at low-angles, whereas the predicted level and the measured results were in good agreement at higher angles. It also was observed that the sea state (SS) did not have a clear effect on average signal strength at higher sea states. The graph does show a definite difference between SS1 and SS6 measurements. This relationship is shown more clearly in Figure 4-6.

This report also states that in any sea state condition there will exist waves of different slopes. The waves will be of varying sizes superimposed. Since there is not likely to be a constant wave-height/slope condition in the vicinity of the buoy, the sea surface surrounding the buoy will at times be characteristic of a range of sea state conditions. This may explain the intermix of recorded signal levels under the higher sea state conditions.

4.4.2 BUOY-TO-SHIP MEASUREMENTS

The measurement range from the Isles of Shoals to Fort Stark provided a fixed reference condition for measurement of sea condition effects on propagation.

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* Project 499 Sea Surveillance Study, Sanders Associates SAN-PAH-66-2231, 15 March 1966, pp. 5-8 to 5-15

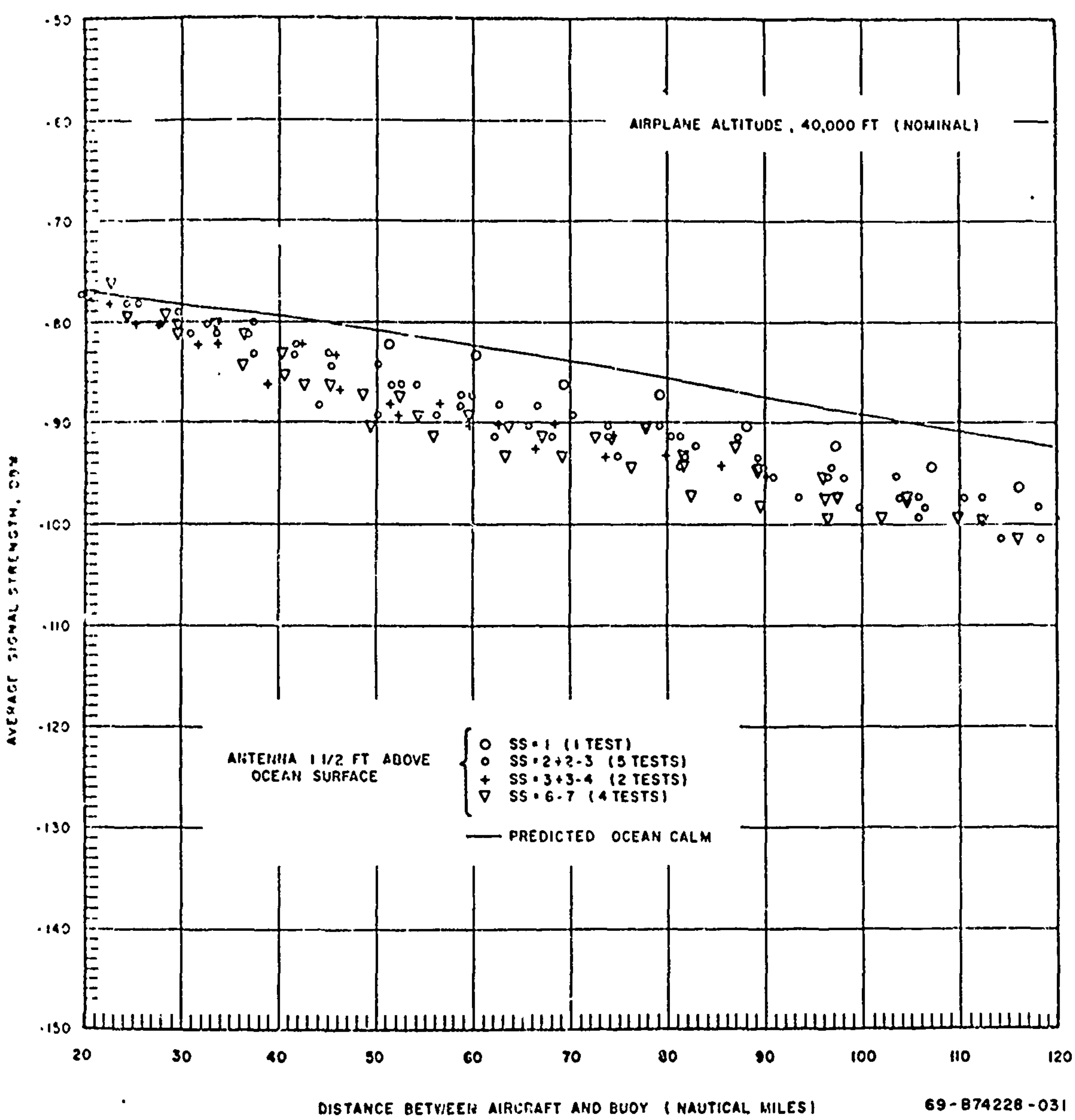

Figure 4-5. Range vs. Signal Strength

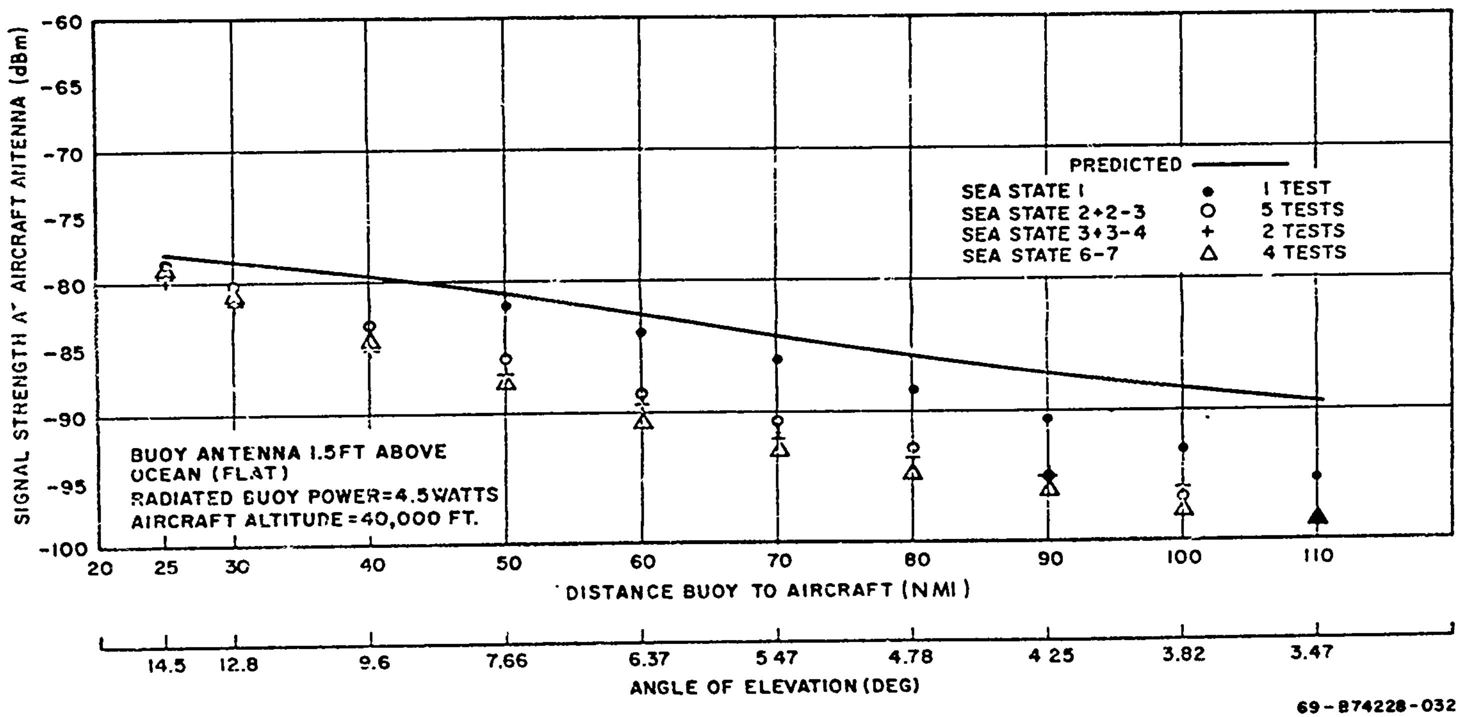

Figure 4-6. Signal Strength vs. Range

However, it was desireable to obtain measurements of signal strength as a function of range. These data points were needed to establish the margin for computer prediction of the propagation loss. We were fortunate in obtaining the cooperation of the U.S. Coast Guard for this phase of the measurements. These measurements are antenna height comparable to the height of the receiving antenna on the Fort Stark blockhouse. The Coast Guard gave permission to conduct these measurements from the Cutter Decisive. This ship has a mast height of 86 feet. The antenna was installed on a yard-arm located on the mast about 80 feet above the sea surface. Metal objects in the vicinity of the antenna did not appear to affect the antenna performance. The coaxial cable from the antenna was fed internally down the mast to the bridge. The receiver, RF volt-meter, command encoder, transmitter, and calibration generator were installed on the bridge. Photographs of the shipboard antenna installation are shown in Figures 4-7 and 4-8.

The test plan required that the Cutter Decisive sail east from Portsmouth, pass north of the Isles of Shoals, and proceed to Jeffreys Ledge, a point 30 nmi from Fort Stark. The command generator aboard the cutter was used to interrogate the buoy a specific distance from Fort Stark. The buoy was located in the water off Fort Stark. Measurements were made only at 30.14 MHz since the other frequencies are not operable beyond line-of-sight.

The received signal strengths recorded during this measurement phase are listed in Table 4-2.

These measurements have been plotted and compared to computer predictions in the following section.

4.4.3 DIFFRACTION ANALYSIS

This analysis[6] was performed to determine the communication reliability that could be expected between sonobuoys and a destroyer in sea conditions up to at least SS4.

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(6) "Sonobuoy/Destroyer Radio Communication Study," Report CR-63-408-3, Radio Corp. of America, December 1963.

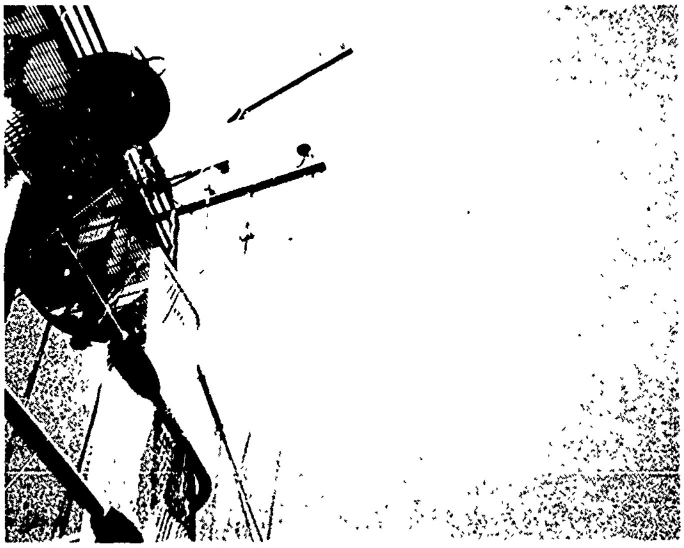

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Figure 4-7. Shipboard Antenna Installation

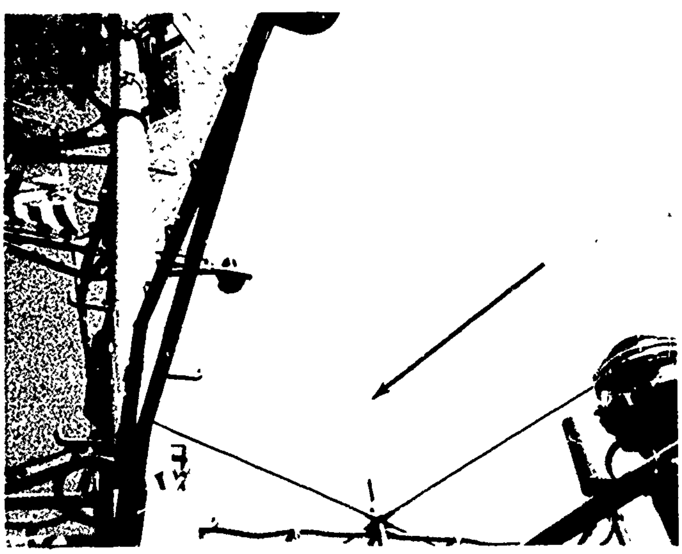

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Figure 4-8. Shipboard Antenna Installation

TABLE 4-2

SIGNAL STRENGTH RECEIVED

BUOY-TO-SHIP

Distance Nautical Miles	Received Signal µV
2	398 - 562
4	196 - 224
5	112 - 141
10	26 - 35
15	11 - 20
20	5.6 - 10
25	4 - 10
30	5.6
Frequency 30.14 MHz	Rec. Antenna 80 ft Trans. Antenna 3 ft

Of particular interest was the observation that a quarter-wave dipole provides a better radiation pattern at low angles than a monopole. The results merely confirmed that which would be obtained with classical diffraction analysis. The resulting reduction in the cutback factor may be significant if the dimensions of the antennas are not too large. The analysis considered that when the buoy was in the through of a wave, the direct radiated signal is blocked by the crest. The signal propagated is diffracted by this crest. Both single and successive diffractions were investigated. Typically, the losses encountered could be predicted as follows:

- A 5-foot wave causes a loss in signal up to 10 dB
- A 10-foot wave causes a loss in signal up to 12 dB
- A 20-foot wave causes a loss in signal up to 15 dB
- Losses are maximum when the buoy is in a through and 0 dB when the buoy rides the crest.

As a comment on this type of analysis, it should be mentioned that the classical well-behaved wave structure is not likely to exist. The formulas for calculating diffraction are varied and have a wide range of output results. The measurements taken in this program did not support the conclusion of 0 dB loss at the crest. Many of the considerations of this analysis are probably factors in the gross variation of signal strength with sea surface conditions; but, the unique distinguishing of any one causitive factor is not possible.

4.5 DATA INTERPRETATION AND COMPARISON

Having summarized the measurement data, computed expected signal levels, and reviewed related measurement programs, we have a sufficient data base against which the measurement results can be interpreted. From Figure 3-5 it is evident that there is wide spread in received signal level. This spread is not solely the result of turbulent sea conditions since the high frequency spread under calm conditions is greater than 20 dB.

There are too many variables and system unknowns to attempt a comprehensive statistical analysis of the data, i.e., determine the mean, the distribution, and probability that a signal level will be exceeded some percentage of operating time. If this were attempted, the confidence level in such a detailed statistical analysis would be low because the range of data recording conditions was limited. Therefore, other approaches have been used to interpret the data.

One way of interpreting the data is to estimate the median signal levels relative to the lowest received levels. The signal variation measured over the 6.5 nmi range from Ft. Stark to the moored buoys has been plotted. This plot (see Figure 4-9) gives an over-view of the range of signal strengths to be expected under different sea conditions.

In Section 3, a number of environmental and physical factors were examined to account for signal variations. Buoy tilt was shown not to be a factor in signal level variation. Likewise the refractive index N, was relatively constant during measurements so that atmospheric conditions were not a significant factor. Also, ducting conditions were not considered to be a factor at the measurement frequencies.

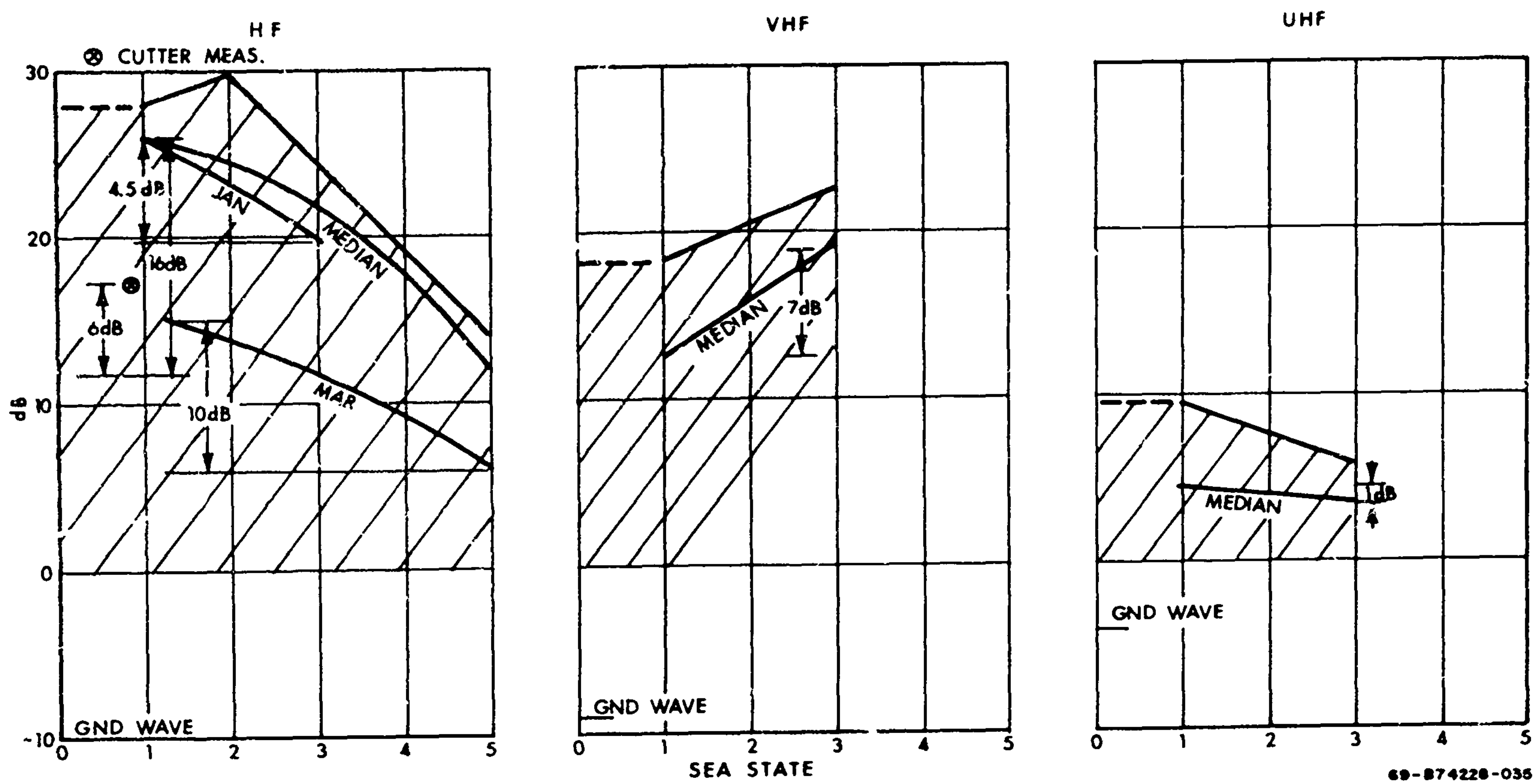

Figure 4-9. Received Signal Levels

The signal variation had some correlation to the accelerometer output. There were no statistical indications that this signal variation was related to buoy position on the wave crests and troughs*. Stronger signals resulted when the buoy was ascending a wave. This condition suggests that the surface from which the indirect wave is reflected differs when a buoy is ascending a wave and when the buoy is descending. This may often be the case both geometrically and in terms of surface roughness. Allowing that waves have no simple configuration, an idealistic configuration may be used to illustrate this point. Figure 4-10 illustrates a moderate SS3 condition where small white caps are beginning to appear.

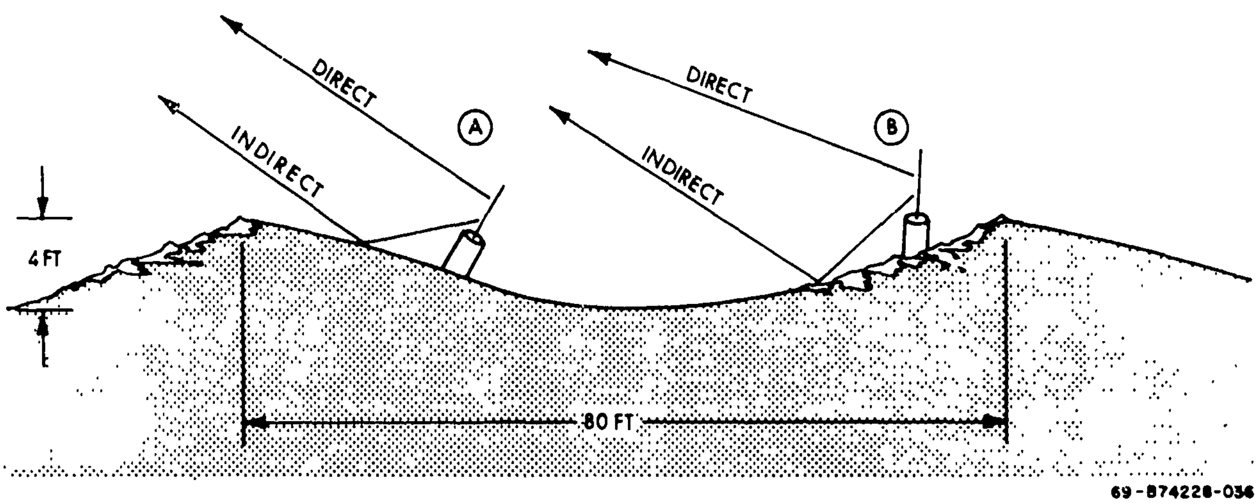

Figure 4-10. Idealized Sea State 3 Condition

Two buoys are shown in the Figure. One, Buoy A, is descending a wave and will have a maximum negative acceleration. The indirect wave from this buoy will have a smoother reflecting surface than Buoy B which is ascending the breaking wave crest. This illustration is only intended to demonstrate

* This does not eliminate the consideration that stronger signals are received from a buoy on a wave crest than from one in a wave trough. Different buoy types with better wave-following characteristics may have this effect.

one concept of why the signal strength differs. Although no definite conclusions can be made, effects such as this are suggested in other studies, (7), (8). A curve illustrating the effect of rough surface conditions (reference (8)) is sh wn in Figure 4-11.

This curve illustrates how the surface reflection coefficient decreases as a function of roughness. A similar concept has been studied by D. Berrick* in his recent work on surface-wave propagation across a rough sea. He relates a change in surface roughness to a different effective surface impedance. This roughness will have the effect of removing energy from the vertical polarized surface-wave and scattering the energy.

The foregoing suggests that there are several conditions which may occur to change the magnitude and relative phase of the indirect wave. The situation is somewhat analogous to the lobing effects encountered with radar antennas. When the direct and indirect waves add in-phase at a distant point, the power is doubled and the voltage is increased by a factor of four. A similar lobing condition exists for an antenna located at the sea surface. At low-angles the direct and indirect wave components are in opposition and the signal is decreased. This effect is referred to as the antenna cutback factor. The effect of the antenna pattern is shown in Figure 4-12, where the patterns have been calculated for antennas operating at three frequencies.

Taking all these effects into consideration, it is difficult to justify more than 12 to 14 dB of signal strength variation. Even under conditions of heavy icing the received signals were higher than predicted. The recorded signal levels were generally higher during the January 20 to 27 period than during the early January, March, and April measurements. Weather and other site conditions

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(7) J. DeLorenzo, "A Study of the Mechanism of Sea Surface Scattering," IEEE Transactions on Antennas and Prop., Sept. 1966

(8) "A Study of Transmission of Weather and Oceanographic Data from Floating Weather Stations," Smyth Research Associates, SRA-416, Oct. 1964

* D. Berrick, paper presented at URSI meeting, April 1969. op. cit.

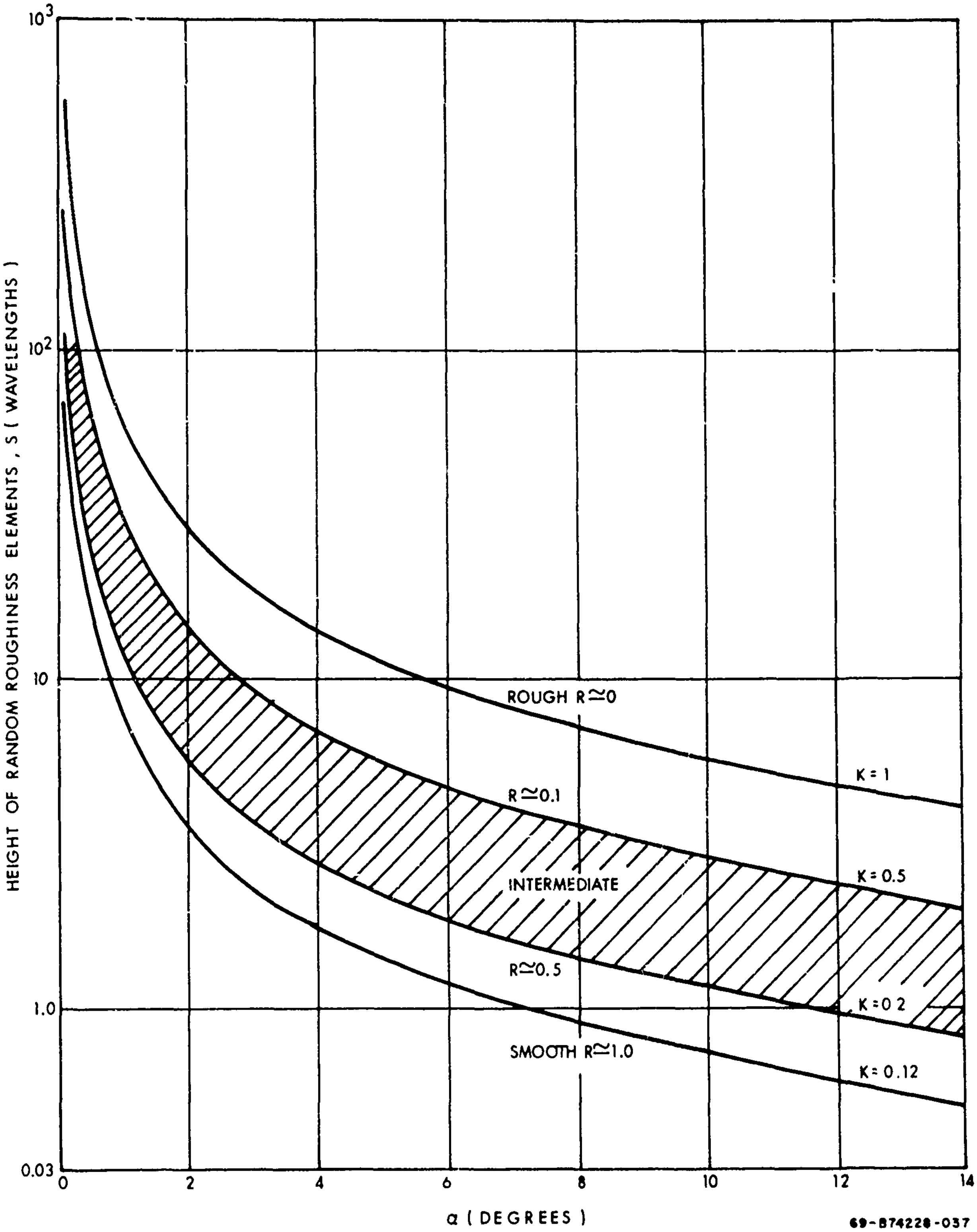

Figure 4-11. Reflecting Surface Roughness Criterion

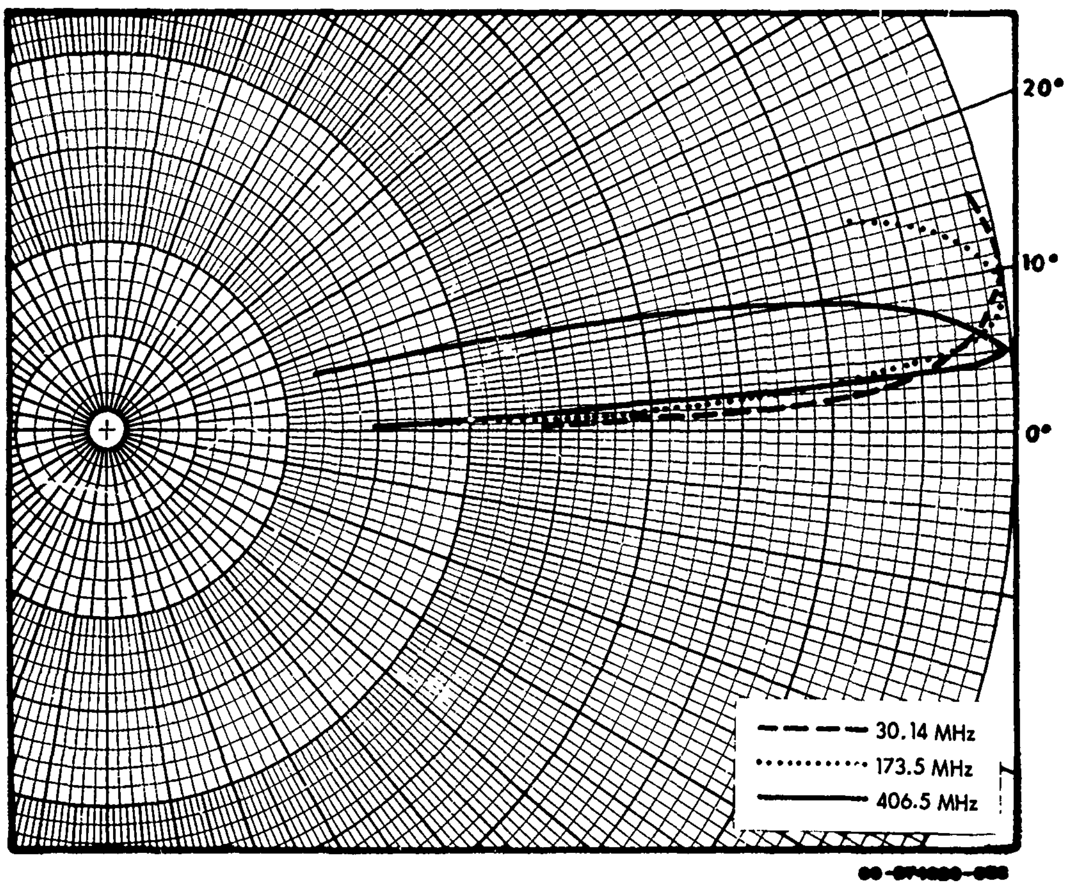

Figure 4-12. Antenna Pattern Behavior

may have been factors; but, there was no definite indication of this. Even during heavy snow and icing conditions, there was no evidence of related signal changes. Since the principle purpose of this program is to provide a method of determining the buoy transmitter power requirement, only the low-level signal strengths are critical. These values and variations with higher state sea conditions will be used to evaluate computer prediction programs.

Two computer prediction programs have been used, GROUNDWAVE and COMTE*. The median measured values taken from the USCGC DECISIVE will be used for comparison. A plot of the computed predictions and the actual measurements is shown in Figure 4-13.** The GROUNDWAVE program prediction is slightly less than the actual measurements***. Two COMTE predictions are shown. The curve for the COMTE program with a 6 dB factor applied is a reasonable approximation of the actual measurements.

The COMTE program uses a 2-ray theory and diffraction theory subroutines in the computation of the line-of-sight transmission loss. It is expected that the ray theory calculation will account for the antenna gain cutback factor experienced at low-angles. Therefore, this 6 dB factor serves to illustrate the change necessary in the COMTE prediction to get nominal agreement with the measurements.

The GROUNDWAVE prediction already has a gain reduction factor included since a 1-mile signal reference is necessary for absolute signal level prediction. A comparison of the dB variation of the predictions relative to the measured values is given in Figure 4-14.

For low-angles of propagation over sea water, the reduction may be difficult to determine. For this reason the GROUNDWAVE program is preferred. A 1-mile reference measurement will be necessary to predict absolute signal levels. Either program may be used to estimate propagation loss over a low-angle or over-horizon path.

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* Authors and source of these programs has been cited in previous sections.

** Prediction programs have been run for 173.5 MHz and 406.5 MHz. Because of the large over-horizon losses at these frequencies only 30.14 MHz is considered for this mode.

*** This prediction uses the equivalent dipole current moment obtained by the 1-mile reference method - see section 4.3.1

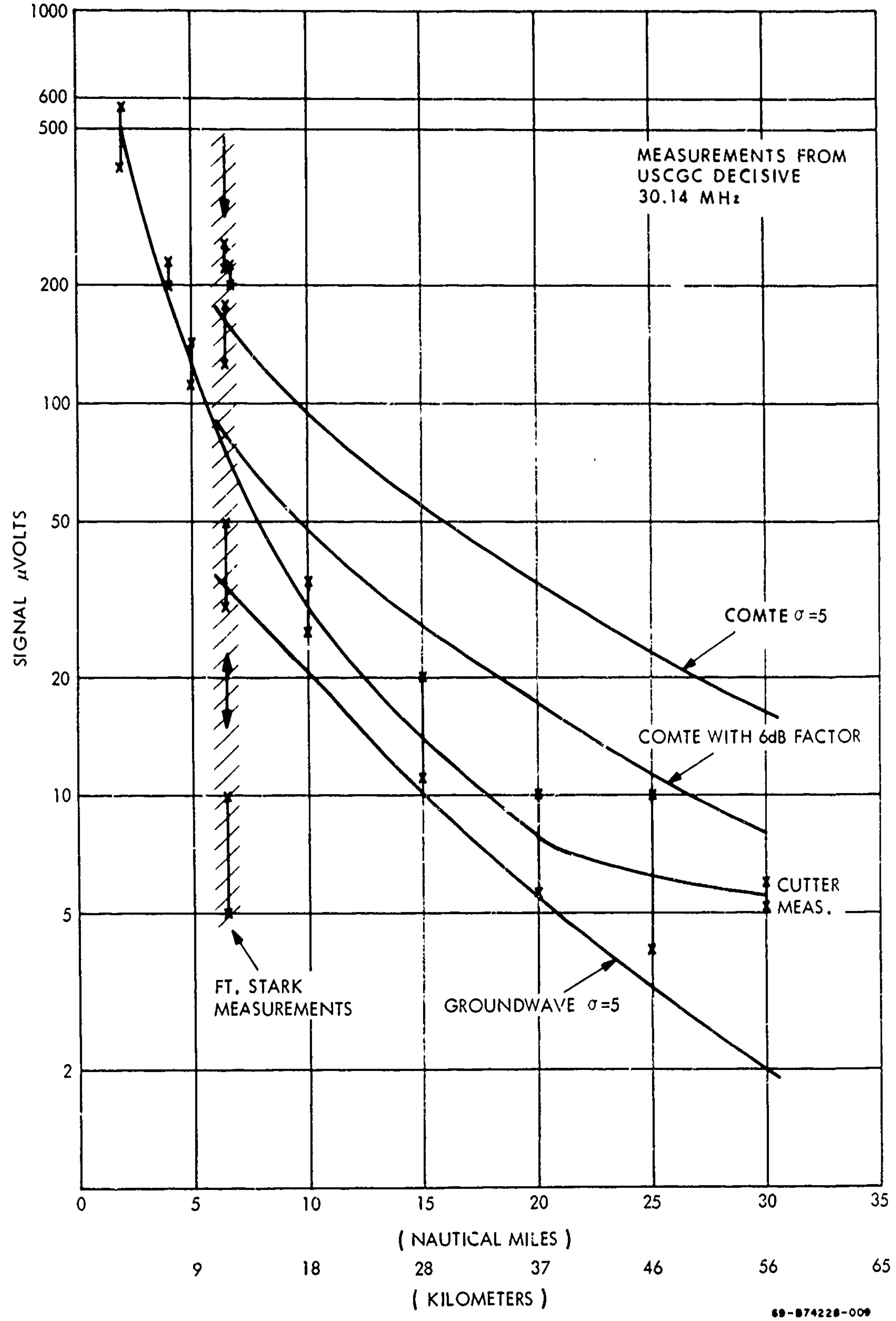

Figure 4-13. Plot of Computer Predictions and Actual Measurements

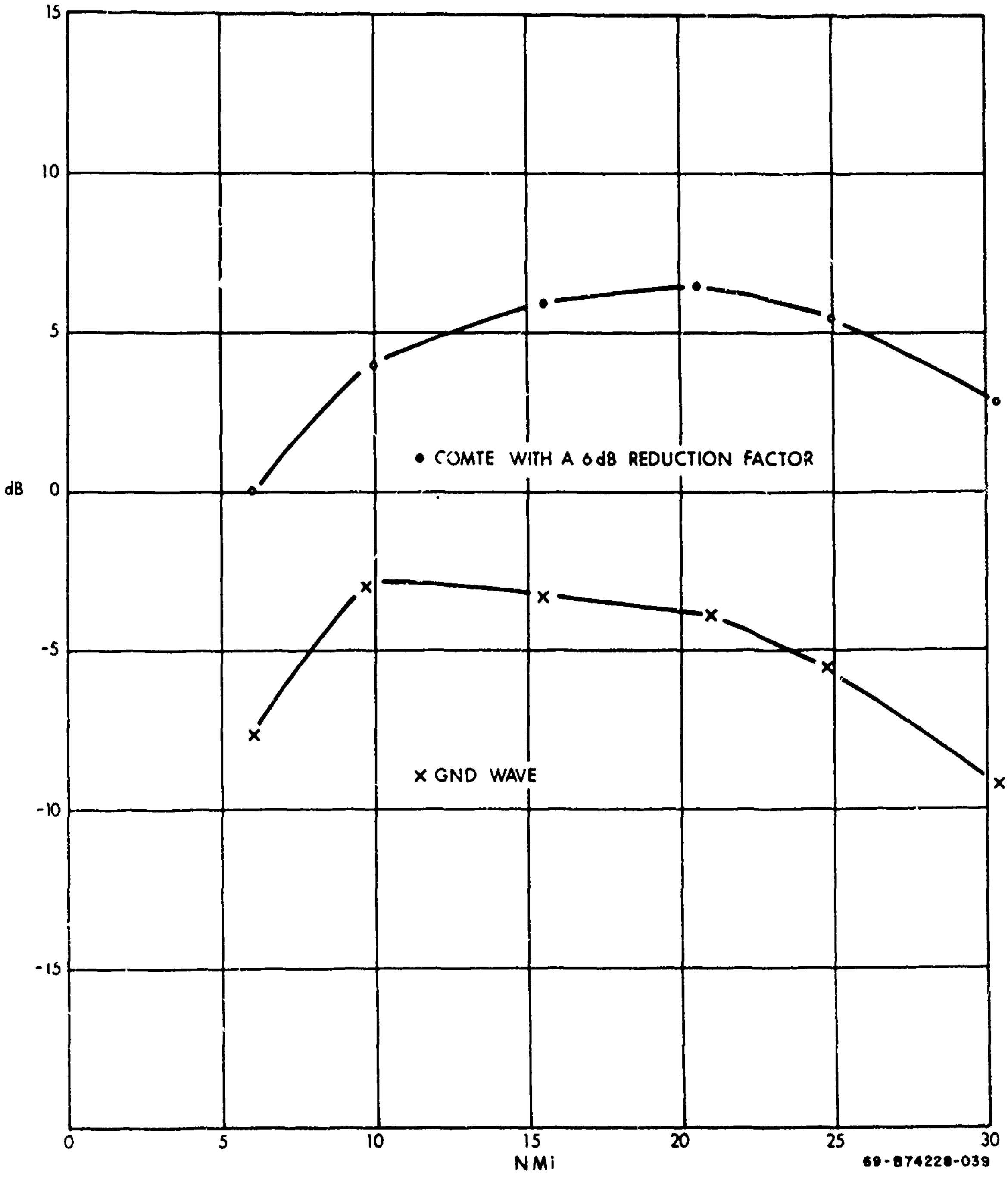

Figure 4-14. Compar'son of Computer Predictions

At SS1 conditions, several of the HF measured values were below the GROUNDWAVE prediction. This will be compensated for by the margin which must be applied to account for higher losses in rough sea conditions.

In estimating the margin for high sea conditions, the following considerations have been included:

- Project 499 measurements showed an 8-9 dB loss due to high sea conditions at low propagation angles (for UHF frequency)
- The diffraction analysis predicted losses from 10 to 15 dB
- The Fort Stark measurements showed a median change of 16 dB over the total measurement period, a 10 dB change during the SS1 to SS5 measurements in March, and a 6 dB change referenced to the Cutter Decisive measurements under rough sea conditions.
- Since the effect of a change of reflection coefficients on the indirect wave seems to be the major effect of sea conditions, the margin will not be considered cumulative. (That is a 6 dB change at 6-1/2 nmi and SS6 does not imply a 60 dB change at 60 nmi.)

From the Fort Stark measurements, a 30.14 MHz signal level change of 10 dB for different sea states referenced to the March measurement seems to be a representative result. Also, at the higher frequencies, the Project 499 measurements and diffraction analysis indicate a margin of 8 dB or higher. One other consideration may be significant in determining a margin to account for sea state effects on received signal level. Running the GROUNDWAVE program for a conductivity of $\sigma = 4$ at 30.14 MHz rather than $\sigma = 5$, produces about a 3 dB change in predicted level. This value changes only slightly with range. If the total path impedance for a surface wave link changes with sea conditions as suggested, then an additional 3 to 4 dB margin would have to be added. This results in an estimated 14 dB total margin for operation at angles less than 10 degrees. However, for this series of measurements the predicted signal levels for the GROUNDWAVE program at over-horizon ranges are at least 4 dB below measured values. Also, since many of the measured signal levels were well above this prediction, a 10 dB margin should be adequate.

Since these other estimations were made at UHF for Project 499 data and VHF for the diffraction analysis, there also is some justification for applying a 10 dB margin at these frequencies to account for sea state conditions. However, it must be remembered that the measurements made at Fort Stark did not indicate a loss of this magnitude in conditions up to SS3, for VHF and UHF frequencies.

SECTION 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 GENERAL

The preceding study* of over-horizon communications between a buoy and an on-water aircraft was based on computer prediction of the propagation loss. The prediction was restricted to smooth sea conditions. An initial design of a buoy for over-horizon operation was presented. The measurements taken in this program are intended to supply an empirical reference for the computer prediction. Using these measurements to evaluate the validity of the prediction for the specific over-water conditions sited, a preliminary buoy design completed in the former study has been re-evaluated.

It was not within the scope of the program to provide a comprehensive analysis of over-water propagation. Such an objective would have required a more detailed investigation of buoy/wave-following characteristics, development of a position-stable antenna platform to eliminate mooring drag and uncontrolled buoy tilting; use of buoy heading sensors, and a means of more accurately determining sea state conditions. Also, measurements for this purpose would require test ranges out to 100 to 200 miles, in areas of different sea water conductivity and varying refractive index. The primary intent has been to determine a reasonable power margin to account for sea conditions and to apply the margin to the buoy design.

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* "Over-Horizon Sonobuoy Communications," Sanders Associates, Inc., April 1968, AD 389741, SAN-JNT-68-1902.

The measurement program has accomplished the objective of providing comparative data on over-water propagation conditions. Curves predicting signal levels using the GROUNDWAVE and COMTE programs at 30.14 MHz referenced to the measurements from the USCGC DECISIVE and Fort Stark are shown in Figure 4-13. Comparison of the measured and predicted curves shows similar rates of signal change but different signal levels. A comparison of terms of dB deviation from the median measured values is shown in Figure 4-14. The difference is about 5 dB, with a maximum deviation of 9 dB. The lower measured values are in very close agreement with the GROUNDWAVE prediction. This program uses a measured 1-mile reference value which accounts for any reduction factor on antenna gain. The COMTE program required an added 6 dB loss factor to approximate the measured values. The use of a conductivity of 4 rather than 5 would improve the prediction of this program. Both programs are based on theory so that exact agreement should not be expected.

Several results of the measurements cannot be satisfactorily explained. The most interesting is the wide range of signal levels (Figure 3-5) measured at 30.14 MHz under relatively calm sea conditions. A calculation of expected signal strength, using only theoretical free space attenuation and no antenna gain reduction or Fresnel zone loss for the antenna, is given below.

Transmitter 14 watts	11.5 dBW
Antenna Gain	-8 dB
	+3.5 dBW
Free space loss	-82.1 dB
	-78.6 dBW
Receiver Antenna Gain	0 dB
	-78.6 dBW
Line Loss	0.9 dB
	-79.5 dBW

This is equivalent to 1.12×10^{-8} watts or 750 μvolts into a 50-ohm load.

This theoretical calculation is 9 dB greater than the highest measured signal levels. Even lower signal levels occurred during moderate weather in March and April (Figure 3-5). Although abnormal refraction conditions were not indicated by the measured humidity and temperature and cannot be confirmed in this case, the measured values at least suggest that some form of refraction effect may have existed. The equipment calibration and checks were believed adequate to eliminate a serious error due to this source. A second result with no clear explanation is the increase in VHF signal level under approximate SS3 conditions. In this case, we can only comment that diffraction situations do not always produce a loss and in some cases a gain occurs. Also the previously suggested change in surface impedance or reflection coefficient under rough sea conditions may produce a smaller indirect wave component.

For HF operation, the curve of Figure 4-9 shows a 16 dB change in median signal level at SS5. Since the lower levels may be due to abnormal propagation, the 10 dB change referenced to the median signal level measurements seems to be a more reasonable change due to sea state.

Computing the GROUNDWAVE program for a conductivity of $\sigma = 4$ shows a difference from $\sigma = 5$ computations of about 3 dB with a very small change as range increases.

RANGE	40 km	61 km	100 km
$\Delta\sigma$	2.8 dB	3.1 dB	3.2 dB

A value of $\sigma = 4$ for conductivity* is the expected value off the New England coast. This value would have resulted in a higher estimate of transmission loss and the comparative values for the GROUNDWAVE prediction shown on Figure 4-13 would have been lower by 3 dB.

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* Conductivity-Appendix C

At ranges out to 200 nmi a 4 dB loss due to conductivity change should be sufficient.

In a prediction of margin to be added to the computer prediction, the following was considered:

- The GROUNDWAVE (1)* program (ref. to one mile) appears to give pessimistic predictions.
- The GROUNDWAVE (2) (ref. radiated power) programs is optimistic
- The COMTE program is optimistic at low propagation angles for over-water predictions
- The 10 dB change with sea conditions probably includes a surface impedance change factor as well as some diffraction loss
- The Project 499 measurements and the diffraction analysis indicated loss of 8 to 9 dB at UHF and 10 dB or more at VHF under their special conditions.

5.2 CONCLUSIONS ON PREDICTION PROGRAM USE

On the basis of these measurements, observations, and a comparison of computer predictions, the following conclusions were reached:

- The COMTE and GROUNDWAVE (ref. radiated power) programs should have 9 dB added to the transmission loss prediction to obtain nominal agreement with the measurements.
- An additional 10 dB loss factor must be included to account for high sea state conditions.

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* The two GROUNDWAVE predictions must be distinguished on the basis of deriving the equivalent dipole current moment. They will be referred to as GROUNDWAVE (1) = ref. to one mile and GROUNDWAVE (2) = referenced to eff. radiated power. The 1-mile reference method and effective radiated power method are discussed in Appendix B and C.

- If the GROUNDWAVE prediction, referenced to one-mile measurements, is used the prediction will be pessimistic and the 10 dB loss margin for high sea state conditions can be discounted by at least 4 to 6 dB. The results are particularly sensitive to the measurement and calculation of the one-mile reference.
- The GROUNDWAVE prediction reference to effective radiated power is recommended for general over-water propagation estimates.

These will apply to all three frequencies. There is less data to support this conclusion at VHF and UHF but in the over-horizon mode, for distances of 100 nmi or more, only HF operation is practical for buoy operations of the type contemplated. COMTE and GROUNDWAVE (2) predictions of propagation loss for low-angle over-horizon operation are given in Figures 5-1 thru 5-4. The curves of the original parametric study, Over-Horizon Buoy Communications - Parametric Design Guide, should have the 4 dB margin added as a sea state factor at low angles of propagation since these curves were computed for $\sigma = 5$.

5.3 RE-ESTIMATE OF PRELIMINARY BUOY DESIGN

The initial design of a buoy for over-horizon operation with an on-water aircraft was considered in the final report* of the Over-Horizon Sonobuoy Communications study. This buoy was a passive-acoustical type which operated for periods up to 96 hours. A maximum range of 200 nmi to an on-water aircraft was required. Other buoy characteristics include:

- Omni-directional acoustical data is processed in the buoy
- Processed data to be transmitted in digital format
- Buoy will have a command receiver to allow functional control
- A beacon or other buoy location aid is to be included

* "Over-Horizon Sonobuoy Communications" Sanders Associates, SNA-JNT-68-1902, AD389741

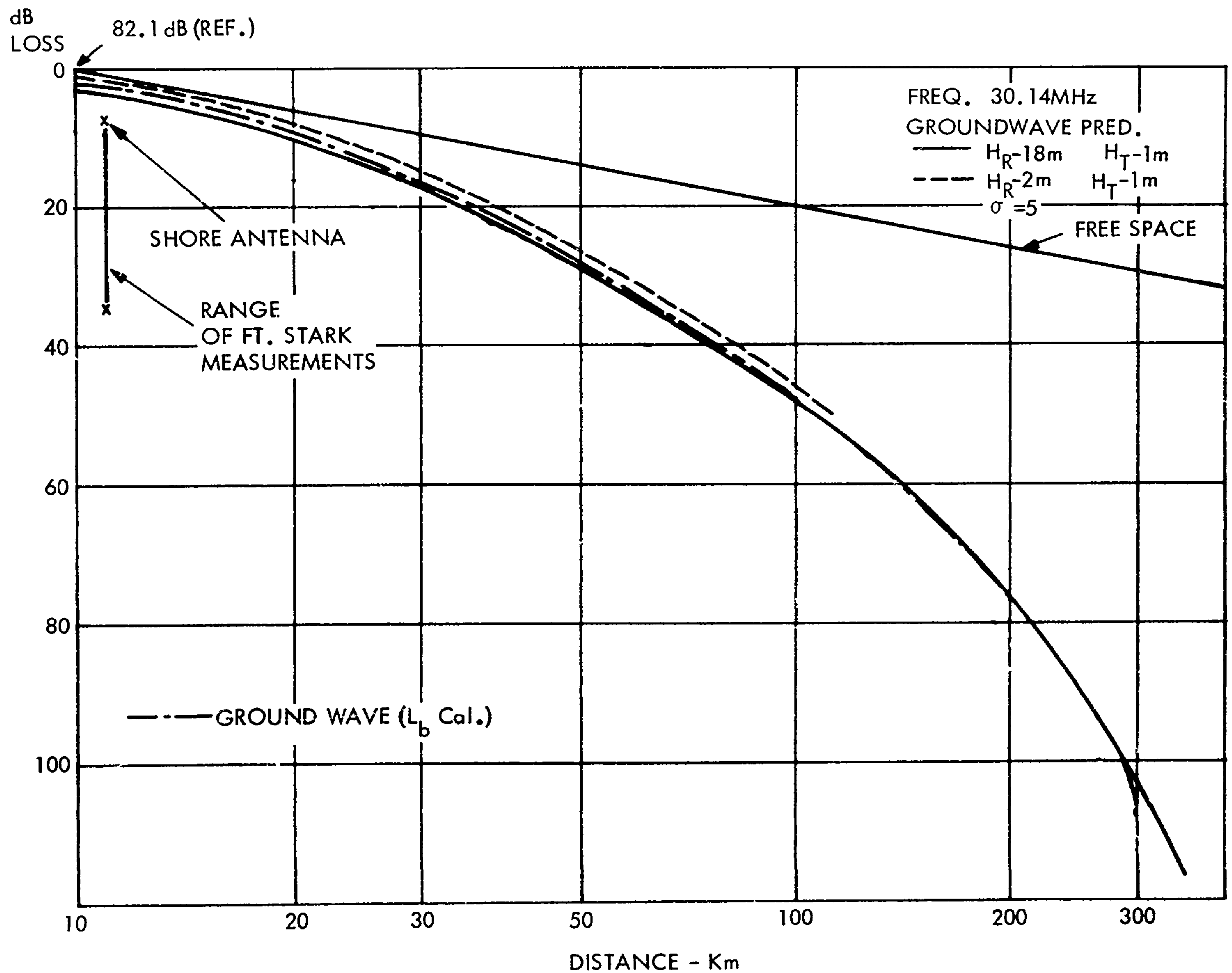


Figure 5-1. Comparison of Computer Predictions

69-874228-001

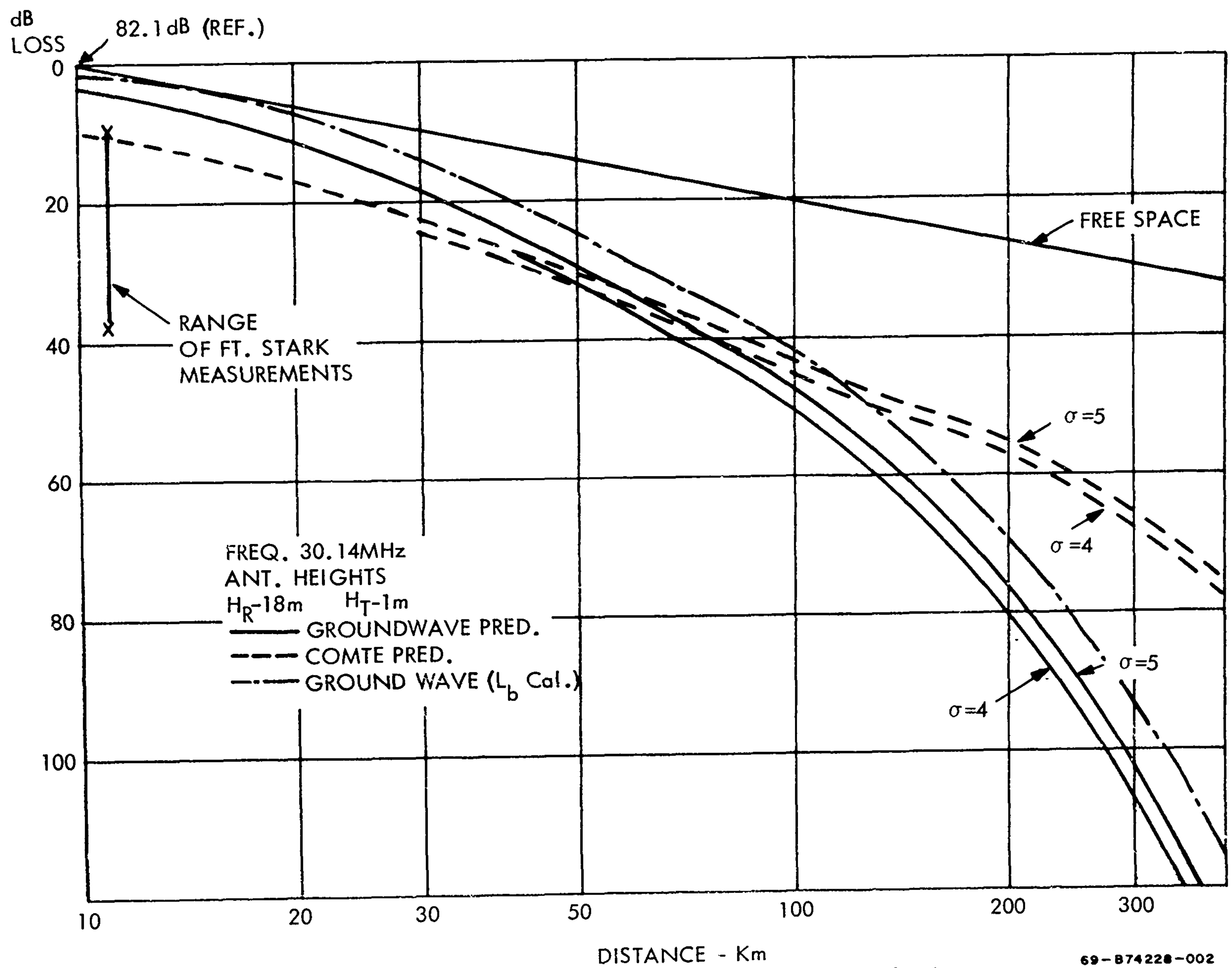


Figure 5-2. Comparison of Computer Predictions

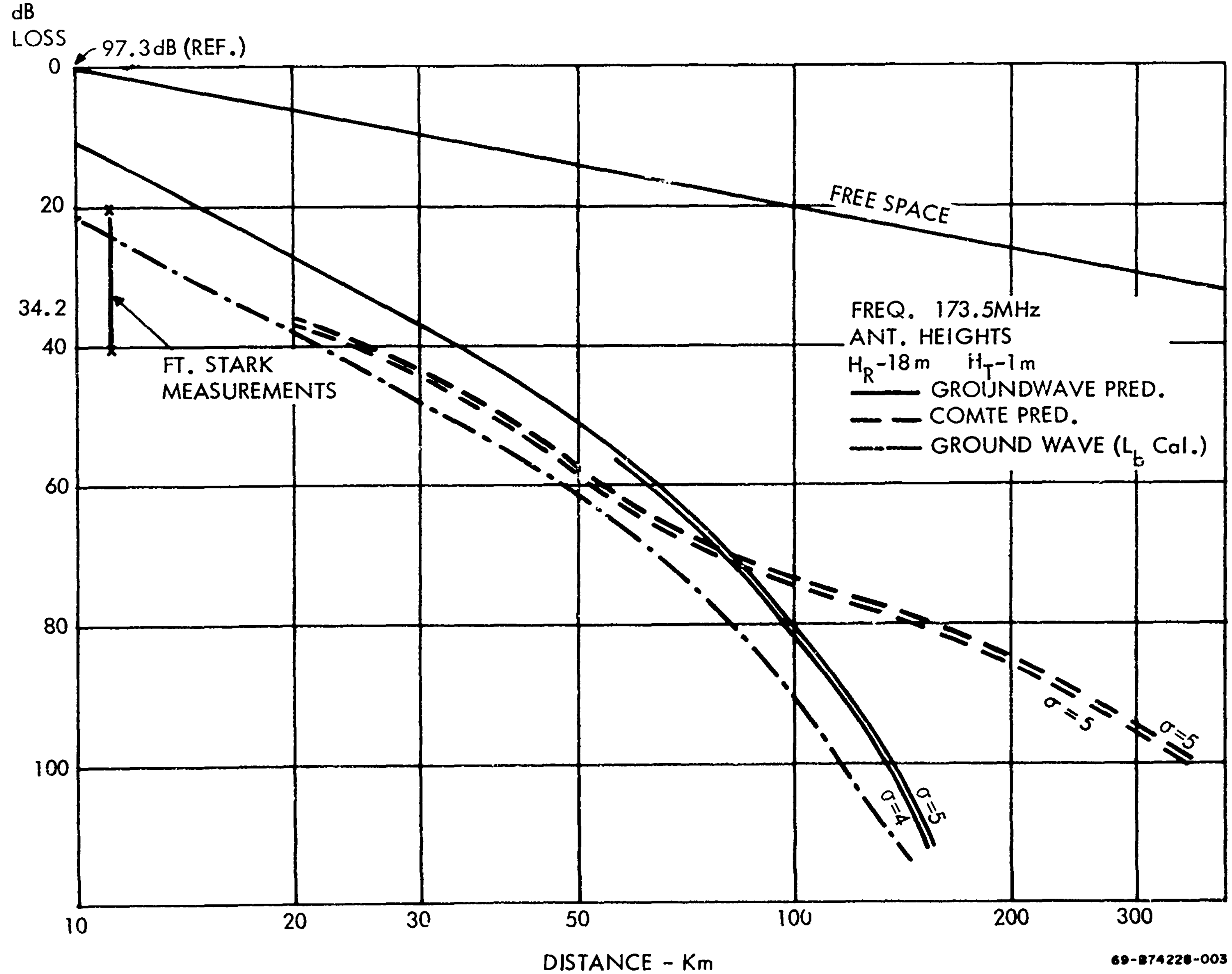


Figure 5-3. Comparison of Computer Predictions

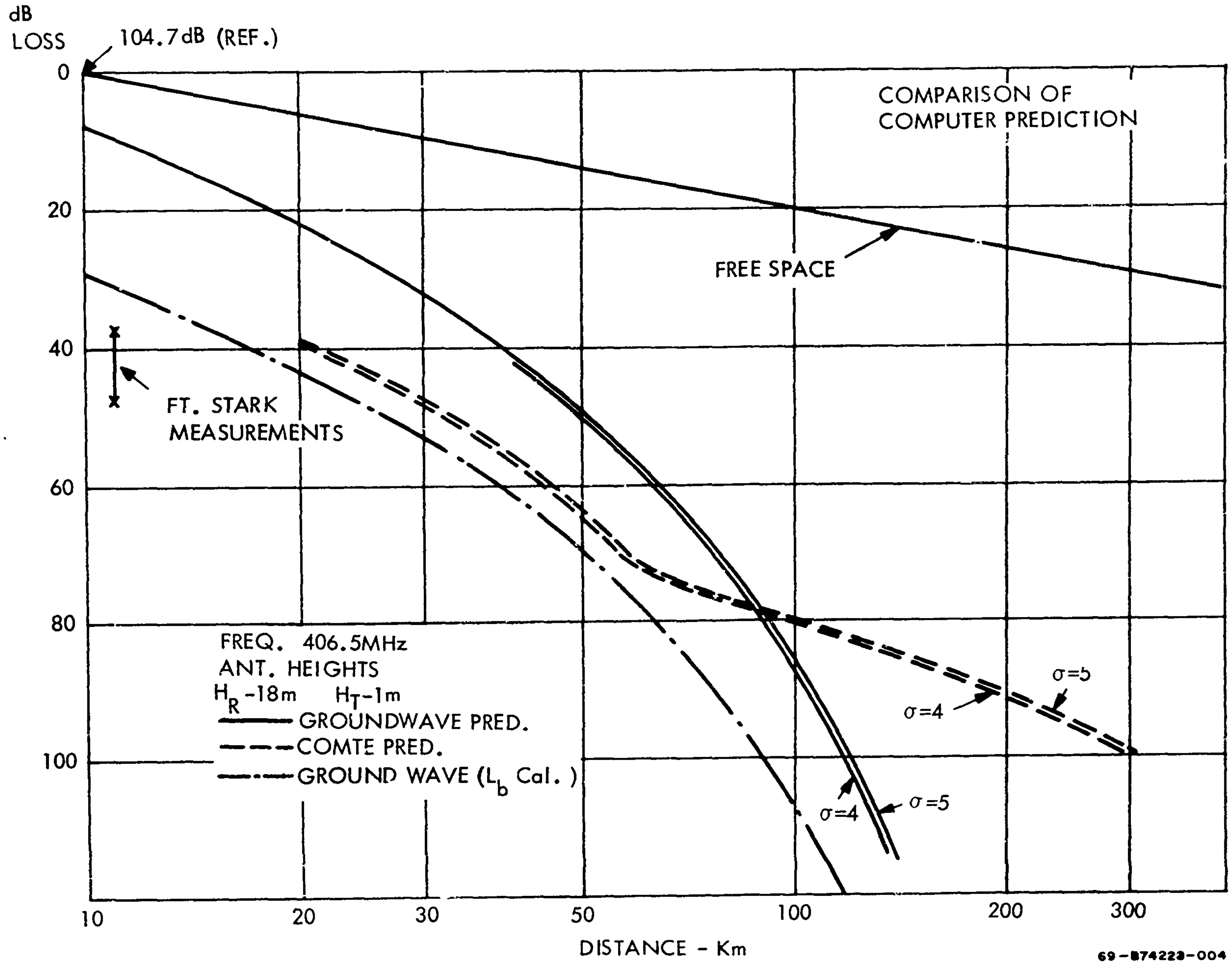


Figure 5-4. Comparison of Computer Predictions

- Three modes of buoy transmission
  - fixed-interval transmission cycled by the monitoring aircraft.
  - response only on command interrogation
  - transmission initiated by in-buoy logic when threshold is exceeded.

Based on these requirements, the transmitter power, control electronics and other buoy components were determined. An estimate was made of buoy size and weight.

Three operating frequencies and modes were considered:

- 1850 kHz Groundwave
- 50 MHz Troposcatter
- 8 MHz Groundwave

It was concluded that the latter frequency was optimum on the basis of power required and antenna efficiency for this type of operation. Recognizing the possibility of interference, a number of operating techniques were suggested to improve this condition.

The initial buoy design estimated that for operation with a 100 Hz data bandwidth a 10-watt transmitter would be required. As a rough comparison, the measured performance of a 30 MHz buoy transmission to the USCGC DECISIVE can be equated to the preliminary 10-watt buoy design. The buoy used in the measurements had a 7-watt transmitter, a 15 kHz bandwidth and the received signal level was 5.6 volts. A comparison can be made based on the relative performance advantages of the 8 MHz buoy design.

This comparison indicates that the original 8 MHz buoy system was 10 dB more conservative than the actual operating buoy system. This is reduced if some of the more difficult to achieve parameters are eased. For example, maintaining the 100 Hz bandwidth would require a phaselock loop-oscillator. The buoy design has been reviewed to incorporate the measurement results.

RELATIVE PERFORMANCE ADVANTAGE

	8 MHz Buoy	30 MHz DECISIVE Buoy	
Frequency	-	Higher Frequency	+11.5 dB
Antenna Difference	-	Less Antenna Gain	+ 5.5 dB
Power Difference	-	Lower Power	+ 2.9 dB
Bandwidth	-	Wider Bandwidth	+21.8 dB
FM Improvement Factor	Smaller Modulation Index	-	-15.0 dB
Range	Larger Range	-	-16.5 dB
			+10.2 dB

From the GROUNDWAVE computer program a prediction of the 8 MHz signal strength at 200 nmi is 2.00×10^{-6} V/m, referenced to a unity dipole current moment. This is converted to transmission loss by the expression:*

$$L_b = 9.0 + 20 \log \frac{f_{kHz}^2}{10^8 /E/}$$

where $/E/ = 2.00 \times 10^{-6}$

$f_{kHz} = 8000$

The transmission loss was calculated to be 119 dB. The required power was determined, using this value:

Sensitivity

Thermal Noise	-204 dBW	
Bandwidth (100 Hz)	20 dB	
Atmospheric & Equipment Noise Factor	60 dB	(Reference: p. 4-108, "Over-Horizon Buoy Communication - Parametric"...)
	-124 dBW	

---

* Converts GROUNDWAVE printout to dB loss, reference L. Berry correspondence.

Power Required

Transmission Loss	119 dB	
Antenna Gains	-2.5 dB	
Prediction Correction Factor	9 dB	(Reference: p. 5-4, this report)
Sea State Margin	10 dB	
Required S/N	8 dB	(Differential PSR modulation for 10^{-3} error rate)
Sensitivity	-124 dBW	
Transmitter Power	20.5 dBW	

In addition, if the bandwidth is increased to 200 Hz so that the frequency stability specification can be eased, 3 dB more power will be required. This total transmitter power will be about 224 watts. Since the transmission duty cycle requirement is estimated at less than 0.01, the added power output can be handled by doubling the battery size (+8.5 lbs and 65 cu in). There has been considerable progress in integrated circuits and packaging since the original size was estimated so that the increase in transmitter size may be compensated by a decrease in other units.

The revised estimate for electronic package of the new buoy design is:

Weight	-	33 lbs
Size	-	273 cu in
Power	-	3.2 Wh

The increase in the electronic package will not require a change in buoy size. However, previous Sanders Associates, Inc. projects in buoy mooring operations of this type have shown advantages for a buoy design having both a subsurface float and a surface float. Because of the antenna height required, this may not be feasible; but, it is anticipated that a longer spar-type buoy may be required. For this reason, the length will be increased. This increase can be accomplished by extending a section of the buoy after mooring. The suggested buoy-shape configuration is not intended to represent a seaworthy design but only to give an indication of a relative size.

The revised buoy design is shown in the following table. Also included for comparison is the original buoy design.

	Buoy Components		Structure and Sea Anchor (lb)	Antenna and Hydrophone (lb)	Total Buoy		
	Vol. (in^3)	Wt. (lb)			Wt. (lb)	Size	Vol. (ft^3)
Previous 8 MHz	264	24.3	100	12	136.3	15"x3'	3.75
New 8 MHz	273	33	155	12	200	15"x5'	6.25

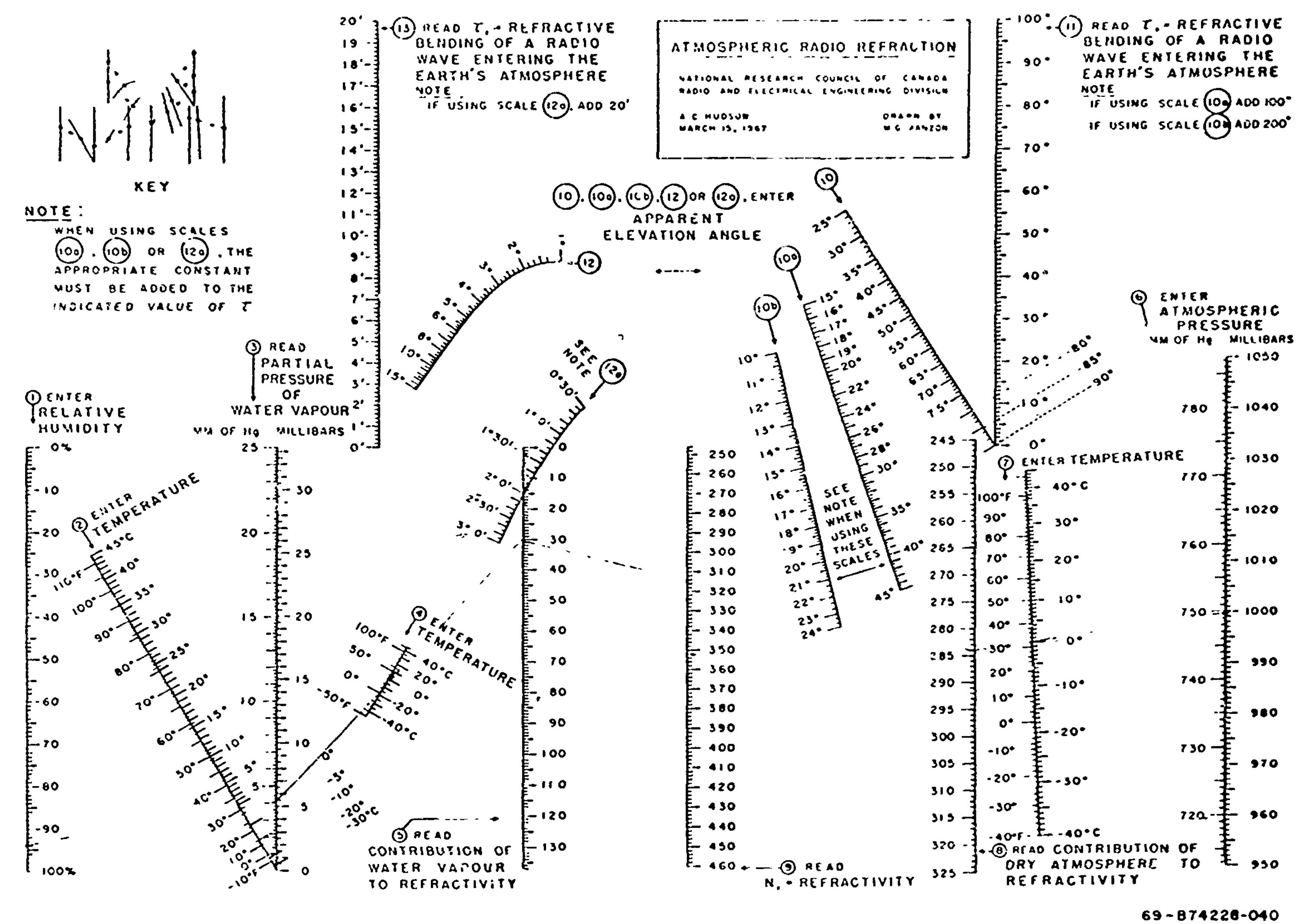
This particular design is preliminary and requires more detailed investigation of frequency stability, bandpass filter tracking, antenna gain performance, and buoy configuration.

If there is future consideration of developing a buoy-system of the type discussed, a long-range verification of the communication link should be conducted. At least three links of 50, 100 and 200 nmi should be established and monitored continuously under well instrumented conditions. The initial measurements should be made over a water path between shore-based installations to control the number of variables.

The measurements have shown a wide variability of signal levels propagating over sea water. This project has supplied valuable data on propagation; but, it has also presented several irregularities which cannot be fully explained without additional tests and analysis. Progress has been made on calibrating computer programs to be used for over-water propagation predictions. But, these unexplained propagation conditions have had to be accounted for by an added signal-power margin. As a result, prediction of over-water transmission loss still requires the use of empirically derived factors rather than a purely computational procedure.

APPENDIX A

NOMOGRAM FOR ATMOSPHERIC RADIO REFRACTION


A. C. Hudson
ATMOSPHERIC RADIO REFRACTION
NATIONAL RESEARCH COUNCIL OF CANADA
RADIO AND ELECTRICAL ENGINEERING DIVISION
A. C. HUDSON
MARCH 15, 1967
DRAWN BY
W. G. JANZON
KEY
NOTE: WHEN USING SCALES (10a), (10b) OR (12a), THE APPROPRIATE CONSTANT MUST BE ADDED TO THE INDICATED VALUE OF τ
(1) ENTER RELATIVE HUMIDITY
(2) ENTER TEMPERATURE
(3) READ PARTIAL PRESSURE OF WATER VAPOUR
MM OF Hg MILLIBARS
(4) ENTER TEMPERATURE
(5) READ CONTRIBUTION OF WATER VAPOUR TO REFRACTIVITY
(6) ENTER ATMOSPHERIC PRESSURE
MM OF Hg MILLIBARS
(7) ENTER TEMPERATURE
(8) READ CONTRIBUTION OF DRY ATMOSPHERE TO REFRACTIVITY
(9) READ N_s - REFRACTIVITY
(10), (10a), (10b), (12) OR (12a), ENTER APPARENT ELEVATION ANGLE
SEE NOTE WHEN USING THESE SCALES
SEE NOTE
(11) READ τ, - REFRACTIVE BENDING OF A RADIO WAVE ENTERING THE EARTH'S ATMOSPHERE
NOTE
IF USING SCALE (10a) ADD 100°
IF USING SCALE (10b) ADD 200°
(13) READ τ, - REFRACTIVE BENDING OF A RADIO WAVE ENTERING THE EARTH'S ATMOSPHERE
NOTE
IF USING SCALE (12a), ADD 20'
69-874228-040

APPENDIX B

CALCULATION OF THE EQUIVALENT DIPOLE CURRENT MOMENT

APPENDIX B

CALCULATION OF THE EQUIVALENT DIPOLE CURRENT MOMENT - ONE MILE REFERENCE

To convert the computer predicted value referenced to unity dipole current moment, calculate $|E_o|$ for each frequency.

$$|E_o| \cong 7.8\,(10^{-7})\, f_{kHz}\ \text{V/m}^{*}$$

$$|E_o| \cong 7.8\,(10^{-7}) \times 30,140 = 235092 \times 10^{-7} = 0.0235\ \text{V/m} = 23.5\text{mV/m}$$

$$|E_o| \cong 7.8\,(10^{-7}) \times 173500 = 0.1353\text{V/m} = 135.3\text{mV/m}$$

$$|E_o| \cong 7.8\,(10^{-7}) \times 406500 = 3170700 \times 10^{-7} = 0.3171\ \text{V/m} = 317.1\ \text{mV/m}$$

$$\text{Equivalent dipole current moment} = \frac{\text{one mile measured value}}{|E_o|}$$

<u>Conversion volts to volts/meter</u>

<u>for 30.14 MHz - roof antenna</u>

Input at receiver = 627 μV at 1-mile range (corrected)**

equivalent field strength is:

$$E_d = \left[\frac{E_w^2}{R_1}\ \frac{R_2}{A}\right]^{1/2}$$

---

* Procedure for calculation given in NBS report 9178, or CIT.

** See Table B-1

E_w = voltage at input to receiver

R_1 = 50 Ω (approximate receiver input resistance)

R_2 = 377Ω (resistance of the medium)

A = Antenna aperature

Antenna gain relative to a dipole -2 dB

then $$A = \frac{1.31\ \lambda^2}{4\ \pi}$$

λ = wavelength at 30.14 MHz = 9.954 meters

$$A = \frac{1.31\ (9.96)^2}{4\ \pi} = 10.33\ m^2$$

$$E_d = \left[\frac{(627 \times 10^{-6})^2\ \ (377)}{(50)\ \ \ (10.33)}\right]^{1/2}$$

$$E_d = \left[0.854\right]\ (627 \times 10^{-6}) = 535.4\ \ \mu V/m$$

Equivalent dipole current moment $= \dfrac{525.4}{23.5 \times 10^3} = 0.0228$

For 30.14 MHz - shore antenna

Input at receiver = 391 µV at 1-mile range (corrected)

equivalent field strength is:

$$E_d = \left[\frac{E_w^2\ \ \ R_2}{R_1\ \ \ A}\right]^{1/2}$$

The relative gain of shore antenna to a dipole is +1 dB

then $$A = \frac{1.84\ \lambda^2}{4\ \pi}$$

$$= \frac{1.84\ (9.954)^2}{4\ \pi} = 14.5\ m^2$$

$$E_d = \left[\frac{(391 \times 10^{-6})^2}{(50)} \frac{(377)}{(14.5)} \right]^{1/2}$$

$$E_d = (0.721)\ (391 \times 10^{-6}) = 282\ \mu V/m$$

$$\text{Equivalent dipole current moment} = \frac{282}{23.5 \times 10^3} = 0.01200$$

<u>For 173.5 MHz</u>

Input at receiver = 356 μV at 1-mile range (corrected)

The antenna gain relative to a dipole is +1.16 dB

then:

$$A = \frac{1.87\ \lambda^2}{4\ \pi}$$

λ = wavelength at 173.5 MHz = 1.73 meters

$$A = \frac{1.87\ (1.73)^2}{4\ \pi} = 0.446\ m^2$$

$$E_d = \left[\frac{(356 \times 10^{-6})^2\ (377)}{(50)\quad (0.446)} \right]^{1/2}$$

$$E_d = (4.11)\ (356 \times 10^{-6}) = 1463.2\ \mu V/m$$

$$\text{Equivalent dipole current moment} = \frac{1463.2}{135.3 \times 10^3} = 0.0108$$

<u>For 406.5 MHz</u>

Input at receiver = 156 μV at 1-mile range (corrected)

The antenna gain relative to a dipole is +5.5 dB

then $$A = \frac{3.06\ \lambda^2}{4\pi}$$

λ = wavelength at 406.5 MHz = 0.738 meters

$$A = \frac{3.06\ (0.738)^2}{4\pi} = 0.133\ m^2$$

$$E_d = \left[\frac{(156 \times 10^{-6})\ (377)}{(50)\ \ \ (0.133)}\right]^{1/2}$$

$$E_d = (7.52)\ (156 \times 10^{-6}) = 1170\ \mu V/m$$

Equivalent dipole current moment $= \dfrac{1170}{317.1 \times 10^3} = 0.0037$

TABLE B-1

REFERENCE 1 MILE

FREQUENCY (MHz)	CONDITION	SIGNAL (μV)	LENGTH (ft)	LOSS (dB)	SIGNAL CORRECTION FOR CABLE LOSS (μV)	AVERAGE TRANS. POWER / REFERENCE POWER (ratio)	SIGNAL CORRECTION FOR CABLE LOSS AND POWER (μV)
30.14	Vert. Roof	400	45	0.9	443	2	627
30.14	Shore	175	330	4.0	276	2	391
30.14	Stoddart Roof	500	45	0.9	-	-	-
30.14	Stoddart Shore	156	330	4.0	-	-	-
173.5	YAGI	200	45	2.3	261	1.86	356
173.5	Stoddart Dipole	175	45	2.3	-	-	-
406.5	Bow Tie	75	45	3.9	107.5	2.1	156
406.5	Stoddart	40*	45	3.9	-	-	-

* Measured value of 20 μV has been corrected to an estimated 40 μV because the stoddart dipole used for the comparison at 406.5 MHz was not equivalent to a standard dipole.

APPENDIX C

DIPOLE CURRENT MOMENT

APPENDIX C

DIPOLE CURRENT MOMENT - RADIATED POWER AND CONDUCTIVITY

$$\frac{2 W_{au}}{I_o^2} = 80 \pi^2 \left(\frac{h}{\lambda}\right)^2 \text{ watts} \qquad (1)$$

dipole current moment referenced to unity current moment $= \left(I_{o_{rms}} h \right) = 18.9 \; \frac{(10^6) (W_{au})}{f}^{1/2}$

f = hertz

W_{au} = power-watts

$(I_{o_{rms}} h)$	
0.940	at 30.14 MHz
0.306	at 173.5 MHz
0.0982	at 406.5 MHz

CONDUCTIVITY

The conductivity of sea water is a variable which changes as a function of temperature and salinity. Typically, the conductivity range is 3 to 5 mhos-per-meter. The conductivity of sea water taken off the coasts of New Jersey and Massachusetts was 4.3 mhos/meter**.

Figure C-1* illustrates the variation of conductivity with temperature and chlorinity. Where chlorinity is related to salinity by:

Salinity = 0.03 + 1.805 x chlorinity

A rough value for the salinity of sea water is 34 ^{o}/oo (parts per thousand) near the surface.

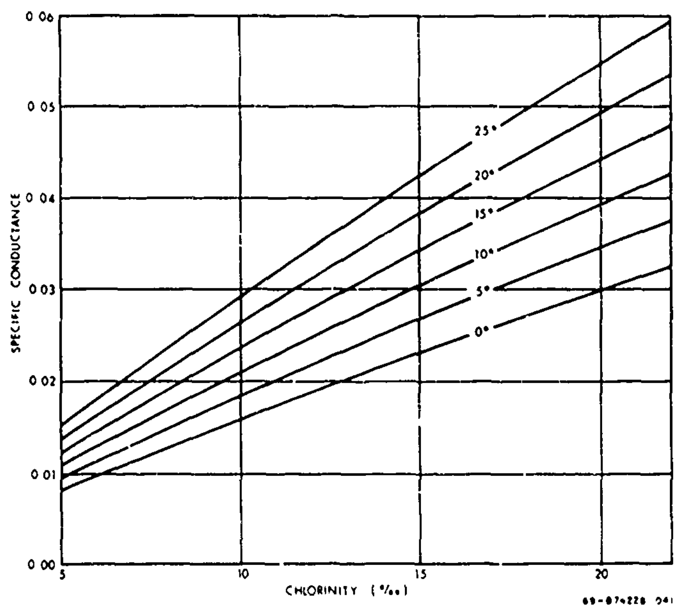


Figure C-1. Specific Conductance of Sea Water as a Function of Temperature and Chlorinity.

(1) Equation given by Ramo & Whinnery, "Fields and Waves in Modern Radio," Wiley, p. 499, for a small dipole

** J. Stratton. "Electromagnetic Theory", p. 606, McGraw-Hill, 1941

* H. Sverdrup, etal, "The Oceans", p. 72

APPENDIX D

COMPUTER PRINTOUTS

CALCULATION OF THE GROUND WAVE
VERTICAL POLARIZATION, FREQUENCY = 30140.00 KC/S.
PERMITTIVITY = 80.00, EARTH CONDUCTIVITY = 5.000 MHOS/M.
HEIGHT OF THE TRANSMITTER = 1.00 M.
HEIGHT OF THE RECEIVER = .002 KM.

F SUB R

DISTANCE KILOMETERS	AMPLITUDE VOLTS/METER	PHASE RADIANS	DISTANCE KILOMETERS	AMPLITUDE VOLTS/METER	PHASE RADIANS	DISTANCE KILOMETERS	AMPLITUDE VOLTS/METER	PHASE RADIANS
10.00	2.28E-03	1.72	43.00	1.34E-04	3.20	73.00	3.07E-05	3.92
13.00	1.53E-03	1.94	46.00	1.14E-04	3.28	76.00	2.71E-05	3.98
16.00	1.09E-03	2.13	49.00	9.65E-05	3.36	79.00	2.39E-05	4.05
19.00	8.01E-04	2.30	52.00	8.22E-05	3.44	82.00	2.12E-05	4.11
22.00	6.08E-04	2.45	55.00	7.04E-05	3.51	85.00	1.89E-05	4.18
25.00	4.71E-04	2.59	58.00	6.06E-05	3.58	88.00	1.68E-05	4.24
28.00	3.71E-04	2.71	61.00	5.25E-05	3.65	91.00	1.50E-05	4.31
31.00	2.97E-04	2.82	64.00	4.56E-05	3.72	94.00	1.34E-05	4.37
34.00	2.41E-04	2.93	67.00	3.98E-05	3.79	97.00	1.21E-05	4.44
37.00	1.97E-04	3.02	70.00	3.49E-05	3.85	100.00	1.08E-05	4.50
40.00	1.63E-04	3.12						

CALCULATION OF THE GROUND WAVE
VERTICAL POLARIZATION. FREQUENCY = 30140.00 KC/S.
PERMITTIVITY = 80.00. EARTH CONDUCTIVITY = 5.000 MHOS/M.
HEIGHT OF THE TRANSMITTER = 1.00 M.
HEIGHT OF THE RECEIVER = 0.02 KM.

E SUR R

DISTANCE KILOMETERS	AMPLITUDE VOLTS/METER	PHASE RADIANS	DISTANCE KILOMETERS	AMPLITUDE VOLTS/METER	PHASE RADIANS	DISTANCE KILOMETERS	AMPLITUDE VOLTS/METER	PHASE RADIANS
10.00	1.61-003	1.30	43.00	1.21-004	3.05	73.00	2.74-005	3.75
13.00	1.20-003	1.54	46.00	1.01-004	3.13	76.00	2.42-005	3.81
16.00	9.28-004	1.74	49.00	8.59-005	3.21	79.00	2.14-005	3.88
19.00	7.28-004	1.94	52.00	7.31-005	3.28	82.00	1.90-005	-2.34
22.00	5.41-004	2.31	55.00	6.26-005	3.35	95.00	1.69-005	-2.28
25.00	4.19-004	2.44	58.00	5.40-005	3.42	88.00	1.51-005	-2.21
28.00	3.30-004	2.56	61.00	4.67-005	3.49	91.00	1.35-005	-2.15
31.00	2.64-004	2.67	64.00	4.07-005	3.56	94.00	1.21-005	-2.09
34.00	2.14-004	2.78	67.00	3.55-005	3.62	97.00	1.08-005	-2.02
37.00	1.75-004	2.87	70.00	3.11-005	3.69	100.00	9.73-006	-1.96
40.00	1.45-004	2.96						

A	B	C	D	E	F	G	H
.500	310.000	5.000	80.000	30.140	1.000	1.000	18.000

D=	10.00	ACR=	9.35
D=	13.00	ACR=	9.95
D=	16.00	ACR=	10.43
D=	19.00	ACR=	10.83
D=	22.00	ACR=	11.20
D=	25.00	ACR=	11.79
D=	28.00	ACR=	12.38
D=	31.00	ACR=	12.96
D=	34.00	ACR=	13.55
D=	37.00	ACR=	14.14
D=	40.00	ACR=	14.73
D=	43.00	ACR=	15.32
D=	46.00	ACR=	15.91
D=	49.00	ACR=	16.50
D=	52.00	ACR=	17.09
D=	55.00	ACR=	17.68
D=	58.00	ACR=	18.27
D=	61.00	ACR=	18.85
D=	64.00	ACR=	19.44
D=	67.00	ACR=	20.03
D=	70.00	ACR=	20.62
D=	73.00	ACR=	21.21
D=	76.00	ACR=	21.58
D=	79.00	ACR=	21.76
D=	82.00	ACR=	21.95
D=	85.00	ACR=	22.13
D=	88.00	ACR=	22.32
D=	91.00	ACR=	22.50
D=	94.00	ACR=	22.69
D=	97.00	ACR=	22.87
D=	100.00	ACR=	23.05

A. SURFACE IRREGULARITY (METERS)
B. REFRACTIVE INDEX
C. CONDUCTIVITY (MHOS/METER)
D. DIELECTRIC CONSTANT
E. FREQUENCY (MHz)
F. POLARIZATION (VERTICAL=1)
G. TRANSMITTING ANTENNA HEIGHT (METERS)
H. RECEIVING ANTENNA HEIGHT (METERS)

A	B	C	D	E	F	G	H
4.000	310.000	5.000	80.000	30.140	1.000	1.000	18.000

D=	10.00	ACR=	9.03
D=	13.00	ACR=	9.61
D=	16.00	ACR=	10.07
D=	19.00	ACR=	10.46
D=	22.00	ACR=	10.82
D=	25.00	ACR=	11.39
D=	28.00	ACR=	11.96
D=	31.00	ACR=	12.53
D=	34.00	ACR=	13.10
D=	37.00	ACR=	13.67
D=	40.00	ACR=	14.24
D=	43.00	ACR=	14.81
D=	46.00	ACR=	15.38
D=	49.00	ACR=	15.96
D=	52.00	ACR=	16.53
D=	55.00	ACR=	17.10
D=	58.00	ACR=	17.67
D=	61.00	ACR=	18.24
D=	64.00	ACR=	18.81
D=	67.00	ACR=	19.38
D=	70.00	ACR=	19.95
D=	73.00	ACR=	20.52
D=	76.00	ACR=	21.09
D=	79.00	ACR=	21.66
D=	82.00	ACR=	21.86
D=	85.00	ACR=	22.04
D=	88.00	ACR=	22.23
D=	91.00	ACR=	22.41
D=	94.00	ACR=	22.59
D=	97.00	ACR=	22.78
D=	100.00	ACR=	22.96

A. SURFACE IRREGULARITY (METERS)
B. REFRACTIVE INDEX
C. CONDUCTIVITY (MHOS/METER)
D. DIELECTRIC CONSTANT
E. FREQUENCY (MHz)
F. POLARIZATION (VERTICAL=1)
G. TRANSMITTING ANTENNA HEIGHT (METERS)
H. RECEIVING ANTENNA HEIGHT (METERS)

CALCULATION OF THE GROUND WAVE
VERTICAL POLARIZATION, FREQUENCY =173500.00 KC/S.
PERMITTIVITY = 80.00, EARTH CONDUCTIVITY = 5.000 MHOS/M,
HEIGHT OF THE TRANSMITTER = 1.00 M,
HEIGHT OF THE RECEIVER = 0.02 KM.

E SUB R

DISTANCE KILOMETERS	AMPLITUDE VOLTS/METER	PHASE RADIANS	DISTANCE KILOMETERS	AMPLITUDE VOLTS/METER	PHASE RADIANS	DISTANCE KILOMETERS	AMPLITUDE VOLTS/METER	PHASE RADIANS
10.00	9.35-004	1.08	43.00	1.63-005	1.84	73.00	2.09-006	2.80
13.00	5.00-004	1.31	46.00	1.30-005	1.93	76.00	1.72-006	2.90
16.00	2.69-004	1.51	49.00	1.05-005	2.02	79.00	1.42-006	3.01
19.00	1.44-004	1.62	52.00	8.48-006	2.11	82.00	1.18-006	3.11
22.00	1.04-004	1.28	55.00	6.89-006	2.21	85.00	9.74-007	3.22
25.00	7.57-005	1.35	58.00	5.61-006	2.30	88.00	8.06-007	3.32
28.00	5.65-005	1.43	61.00	4.59-006	2.40	91.00	6.68-007	3.43
31.00	4.29-005	1.50	64.00	3.74-006	2.50	94.00	5.56-007	3.53
34.00	3.32-005	1.58	67.00	3.09-006	2.60	97.00	4.60-007	3.64
37.00	2.63-005	1.65	70.00	2.54-006	2.70	100.00	3.82-007	3.74
40.00	2.04-005	1.75						

A	B	C	D	E	F	G	H
4.000	310.000	5.000	80.000	173.500	1.000	1.000	18.000

D=	10.00	ACR=	21.81
D=	13.00	ACR=	24.24
D=	16.00	ACR=	26.49
D=	19.00	ACR=	28.61
D=	22.00	ACR=	30.59
D=	25.00	ACR=	31.76
D=	28.00	ACR=	32.92
D=	31.00	ACR=	34.09
D=	34.00	ACR=	35.26
D=	37.00	ACR=	36.43
D=	40.00	ACR=	37.60
D=	43.00	ACR=	38.77
D=	46.00	ACR=	39.94
D=	49.00	ACR=	41.11
D=	52.00	ACR=	42.28
D=	55.00	ACR=	43.45
D=	58.00	ACR=	44.61
D=	61.00	ACR=	45.78
D=	64.00	ACR=	46.95
D=	67.00	ACR=	48.12
D=	70.00	ACR=	49.29
D=	73.00	ACR=	50.46
D=	76.00	ACR=	51.63
D=	79.00	ACR=	51.91
D=	82.00	ACR=	52.09
D=	85.00	ACR=	52.28
D=	88.00	ACR=	52.46
D=	91.00	ACR=	52.65
D=	94.00	ACR=	52.83
D=	97.00	ACR=	53.01
D=	100.00	ACR=	53.20

A. SURFACE IRREGULARITY (METERS)
B. REFRACTIVE INDEX
C. CONDUCTIVITY (MHOS/METER)
D. DIELECTRIC CONSTANT
E. FREQUENCY (MHz)
F. POLARIZATION (VERTICAL=1)
G. TRANSMITTING ANTENNA HEIGHT (METERS)
H. RECEIVING ANTENNA HEIGHT (METERS)

CALCULATION OF THE GROUND WAVE
VERTICAL POLARIZATION, FREQUENCY =406500.00 KC/S.
PERMITTIVITY = 80.00, EARTH CONDUCTIVITY = 5.000 MHOS/M,
HEIGHT OF THE TRANSMITTER = 1.00 M.
HEIGHT OF THE RECEIVER = 0.02 KM.

E SUB R

DISTANCE KILOMETERS	AMPLITUDE VOLTS/METER	PHASE RADIANS	DISTANCE KILOMETERS	AMPLITUDE VOLTS/METER	PHASE RADIANS	DISTANCE KILOMETERS	AMPLITUDE VOLTS/METER	PHASE RADIANS
10.00	9.79-004	0.48	43.00	1.66-005	1.48	73.00	1.24-006	2.80
13.00	5.12-004	0.52	46.00	1.27-005	1.60	76.00	9.66-007	2.93
16.00	3.07-004	0.54	49.00	9.70-006	1.73	79.00	7.52-007	3.07
19.00	2.03-004	0.59	52.00	7.45-006	1.86	82.00	5.86-007	3.21
22.00	1.43-004	0.70	55.00	5.73-006	1.99	85.00	4.57-007	3.35
25.00	1.01-004	0.80	58.00	4.43-006	2.12	88.00	3.56-007	3.49
28.00	7.22-005	0.90	61.00	3.42-006	2.25	91.00	2.78-007	3.63
31.00	5.27-005	1.01	64.00	2.65-006	2.39	94.00	2.17-007	3.77
34.00	3.90-005	1.12	67.00	2.06-006	2.52	97.00	1.69-007	3.91
37.00	2.91-005	1.23	70.00	1.60-006	2.66	100.00	1.32-007	-2.24
40.00	2.19-005	1.35						

A	B	C	D	E	F	G	H
4.000	310.000	5.000	80.000	406.500	1.000	1.000	18.000

D=	10.00	ACR=	24.92
D=	13.00	ACR=	27.03
D=	16.00	ACR=	28.87
D=	19.00	ACR=	30.52
D=	22.00	ACR=	32.05
D=	25.00	ACR=	33.58
D=	28.00	ACR=	35.10
D=	31.00	ACR=	36.63
D=	34.00	ACR=	38.15
D=	37.00	ACR=	39.68
D=	40.00	ACR=	41.20
D=	43.00	ACR=	42.73
D=	46.00	ACR=	44.25
D=	49.00	ACR=	45.77
D=	52.00	ACR=	47.30
D=	55.00	ACR=	48.82
D=	58.00	ACR=	50.35
D=	61.00	ACR=	51.87
D=	64.00	ACR=	53.40
D=	67.00	ACR=	54.92
D=	70.00	ACR=	56.45
D=	73.00	ACR=	57.63
D=	76.00	ACR=	57.79
D=	79.00	ACR=	57.94
D=	82.00	ACR=	58.10
D=	85.00	ACR=	58.25
D=	88.00	ACR=	58.40
D=	91.00	ACR=	58.56
D=	94.00	ACR=	58.71
D=	97.00	ACR=	58.87
D=	100.00	ACR=	59.02

A. SURFACE IRREGULARITY (METERS)
B. REFRACTIVE INDEX
C. CONDUCTIVITY (MHOS/METER)
D. DIELECTRIC CONSTANT
E. FREQUENCY (MHz)
F. POLARIZATION (VERTICAL=1)
G. TRANSMITTING ANTENNA HEIGHT (METERS)
H. RECEIVING ANTENNA HEIGHT (METERS)

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4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Report

5 AUTHOR(S) (Last name, first name, initial)

Cullen, Francis

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13 ABSTRACT

Report describes results of a program of measurement and analysis of RF signal propagation. The work supplements previous investigations related to over-water RF propagation. The purpose of this program was to provide improved predictions of propagation loss on over-water paths. Primary application was over-horizon propagation using surface-wave mode. Measurements were made to substantiate prediction procedures. Measurements were made using buoys instrumented to telemeter data to the receiving station. This data and sea state conditions were used in analysis of measurements. Computer prediction techniques were evaluated on basis of measurements. Received signal strengths were used to evaluate computer prediction methods. Signal variations were used to estimate compensating power margin for propagation calculations. Results were applied to design of a buoy transmitting over-horizon to distances of 200 nautical miles.

DD FORM 1 JAN 64 1473

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
PROPAGATION MEASUREMENTS						
OVER-WATER						
LOW-ANGLE						
OVER-HORIZON						
SONOBUOY COMMUNICATION						

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