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13. ABSTRACT

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Modifications of vertical antennas, including shielding of the leading edge and improved base insulators, reduced but did not solve the problem. An experimental NRL-designed-and-constructed crossed-loop antenna system improved reception characteristics with respect to both wetting and static pickup. NRL has evaluated the performance of modified vertical antennas and crossed-loop antennas in the laboratory and on Omega test flights. These flight tests have revealed that the crossed-loop antenna offers adequate sensitivity and a significant reduction of precipitation effects and thus provides all-weather operation of Omega aircraft receivers.

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CONTENTS

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PROBLEM STATUS

This is the final report on one phase of the study of Omega aircraft receivers at NRL.

AUTHORIZATION

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PRECIPITATION EFFECTS ON OMEGA AIRCRAFT RECEIVERS

INTRODUCTION

Omega is a hyperbolic very-low-frequency (vlf) radio navigation system characterized by very long range and an accuracy on the order of 1 to 2 mi with respect to earth coordinates. The Omega system is fully described in Ref. 1, and earlier aircraft receiver work done at the Naval Research Laboratory (NRL) is described in Refs. 2 through 5. In a single-frequency Omega receiver, the hyperbolic lines of position (i.e., lanes) are ambiguous every 8 naut mi on the baseline between two stations. In two- and three-frequency receivers, the lane width increases to 24 and 72 naut mi, respectively (2). It is thus essential, particularly with airborne Omega receivers, to maintain a knowledge of aircraft position for purposes of lane identification within a minimum of 4 and a maximum of 36 naut mi (or one-half lane) during periods of Omega signal loss.

The first Omega aircraft receiver developed at NRL, the Mark I, was flight tested from 1961 to 1963. Using a vertical electric-field antenna (vertical wire or blade antenna), the Mark I experienced Omega signal loss in areas of high atmospheric noise and particularly during periods of precipitation when static discharges and other precipitation effects on the aircraft occurred. Improvements in receiver design (NRL Mark II Omega receiver) alleviated but did not eliminate the problem. On many flights, precipitation static caused the loss of all Omega signals even when flying within several miles of one of the Omega transmitters. In 1965, NRL undertook the development of a crossed-loop antenna which would, in theory, reduce the reception of near-field electrostatic interference due to its magnetic dipole characteristics. The antenna was coupled to the NRL Mark II Omega aircraft receiver in 1966 and flight tested in a rainstorm south of Puerto Rico. While Omega signals from the vertical electric-field antenna were unreceivable due to precipitation static interference, signals from the crossed-loop antenna showed no deterioration. Later flight tests further supported these results. The NRL Mark III Omega Aircraft Navigation Set, using a commercially produced crossed-loop antenna, experienced no signal deterioration during a 3-hour North Atlantic storm, while Loran A, Loran C, and hf communications on board the NRL aircraft were all disrupted by precipitation static for the entire 3-hour period.

A brief chronology of NRL progress in the elimination of precipitation effects on Omega aircraft receivers is given below

1961-1962 - High noise and precipitation static effects caused erratic servo response and loss of lanes in the NRL Mark I Omega aircraft receiver.

1962-1963 - The narrowband rf amplifiers of the Mark I were replaced with wideband, hard-limiting circuits. This yielded some improvement in performance, but Omega lanes were still lost in precipitation.

1964-1965 - Addition of automatic signal cutout and dead reckoning in the NRL Mark II receiver permitted longer periods of signal loss without lane loss during periods of high noise, but lanes were still lost during extended periods of precipitation.

1965-1966 - The NRL crossed-loop antenna was designed, developed, and flight tested in Puerto Rico. No perceptible deterioration of Omega signals in precipitation static occurred.

1966-1968 - Further improvement and evaluation of electric-field antennas and crossed-loop antennas were accomplished. Improvements in electric-field antennas still did little to eliminate the precipitation static problems occurring with these antennas.

October 1968 - The NRL Mark III Omega Aircraft Navigation Set was successfully flown across the North Atlantic and back. Utilizing a crossed-loop antenna, the system provided continuous navigation even when under severe precipitation conditions.

EARLY STUDIES OF PRECIPITATION EFFECTS

The NRL Mark I Omega aircraft receiver used narrowband, high-Q, rf amplifiers with no limiting. Under high noise conditions, especially in precipitation static conditions, signals and lanes were frequently lost by the Mark I receiver. The first modification to improve this condition was the replacement of the narrowband, high-Q circuits in the rf section of the receiver with wideband hard-limiting circuits. A noticeable improvement was obtained, but heavy precipitation still caused lane loss in the Mark I receiver when high-noise inputs generated an erratic response in the phase servos.

A rather graphic experience with the Mark I in precipitation static conditions occured on a flight from Puerto Rico to Washington in 1961 in an EC121K aircraft. The aircraft penetrated a weather front containing large hailstones which were of sufficient size and quantity to damage the aircraft radomes. Figure 1 is a strip-chart recording of the two lines of position (lop's) which were being tracked. On this particular flight no external rate-aiding was used. However, the type-II-servo tracking channels included an integrator loop with a time constant of about 7 min. The early portion of the flight shows stable, consistent tracking. The aircraft heading was essentially constant over the area of interest. At about 1445Z the aircraft entered the storm front; in the following 5 min several lanes were lost, *not* because of a gradual phase slip but because of a radical offset in the receiver tracking, apparently caused by noise driving the servos off the track in a given direction. After the aircraft passed the storm front, tracking returned to normal. The antenna being used at this time was a 6-ft vertical wire inside the large upper radome of the aircraft; therefore, no particles were striking the antenna, and the antenna was not wetted. Conventional wick-type static dischargers were mounted on the aircraft.

When the Mark II was designed, automatic rate-aiding circuits were added and an additional antistatic concept was incorporated. An AGC-type circuit senses a low S/N ratio and during periods of high noise, causes the receiver to open the rf input to the phase detector and to dead reckon on stored wind velocities and rate-aiding inputs from the compass and true airspeed computer on board the aircraft.

Over a period of several months in 1965, the Mark II overall flight time, the flight time in precipitation static, and the flight time in automatic dead reckoning (when the S/N ratio measured by the AGC system was judged to be inadequate for normal tracking) were recorded and are given here. During much of this period only two of the three Omega stations (Hawaii, New York, and Criggion, Wales) were in operation. This record covers a period of about one year during which all periods of flight through precipitation areas were noted. Further details are recorded in Ref. 3.

Total flight time, 227 hours

Total precipitation time, 6.75 hours

Total dead reckoning (due to precipitation), 1 hour

Ratio of precipitation conditions to flight time $\frac{6.75}{227} = 3\%$

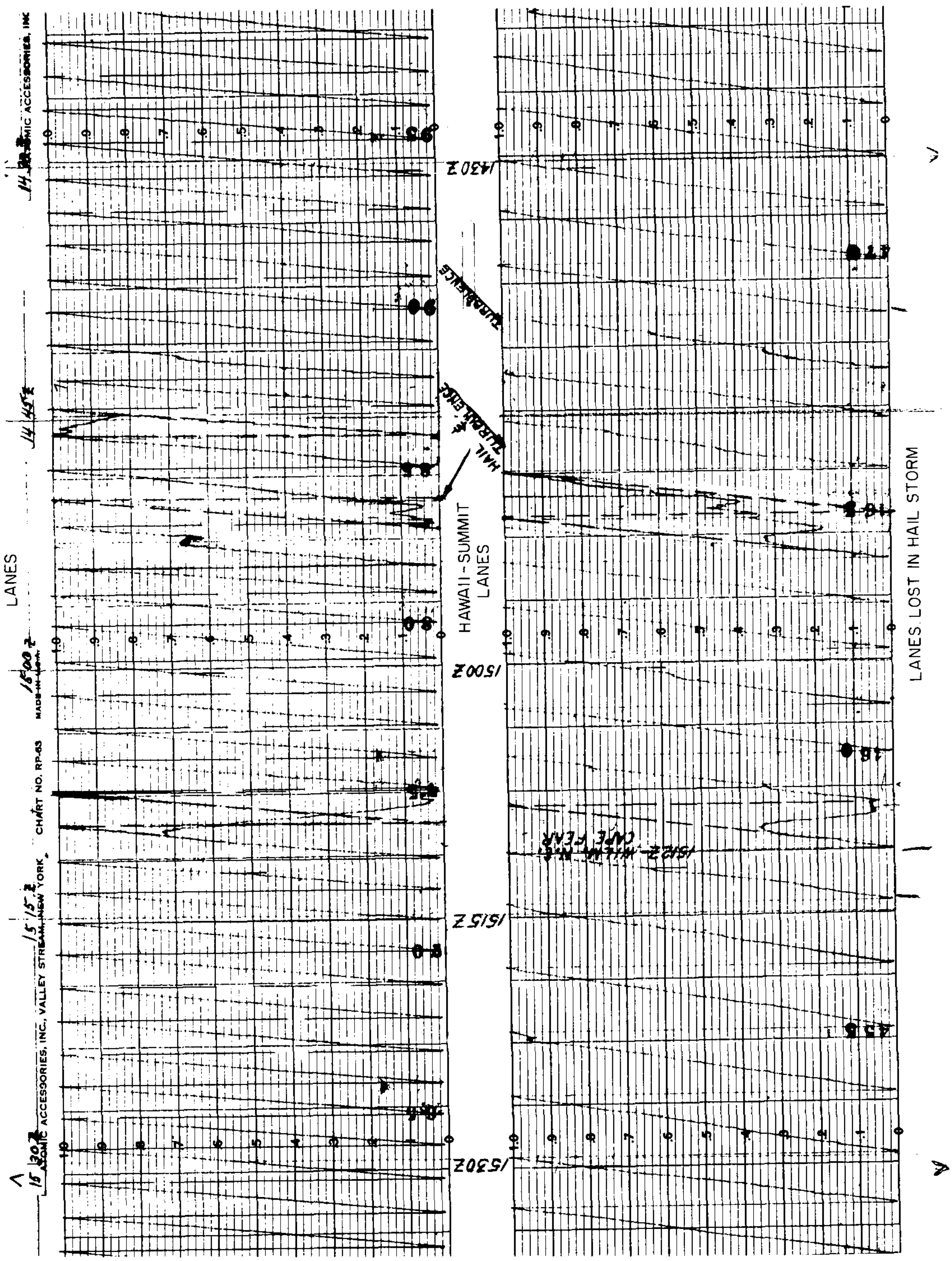

Fig. 1 - Omega receiver lanes of position during hailstorm; phase vs time (minutes)

Ratio of dead reckoning to precipitation time $\frac{1}{6.75} = 15\%$

Ratio of dead reckoning time to flight time $\frac{1}{227} = 0.44\%$

These data should not be considered separately. They have been gathered in areas of reasonably high signal level and mostly in periods of normally fair weather. If one considers the ratio of dead reckoning due to precipitation to the flight hours in precipitation and the fact that even slight amounts of precipitation were recorded as precipitation conditions, the precipitation static problem becomes more severe than it appears at first glance. As a comparison, the NRL Mark III Omega receiver with a crossed-loop antenna in a 1968 flight flew through 3 hours of continuous, severe precipitation without signal loss from any Omega station.

At this point (in 1966), the Mark II aircraft receiver with the vertical antenna was considered to be operational for aircraft, but it was certainly desirable that a greater effort be made to investigate the causes of signal loss in precipitation static. The Mark II was not alone in experiencing precipitation problems. The British, in an article in "Aviation Week" (March 6, 1961), made the following comment concerning their vlf flights:

> "Noise does cause trouble, especially that which is due to tropical thunderstorms. On a flight to Nairobi from Farnborough the Rugby signal was intermittently swamped but occasional glimpses of the signal proved enough to maintain course."

The Decca system has had similar trouble, at least with propeller aircraft at low altitudes; and in the only jet flight with the Mark II receiver operating with the 2-ft blade antenna, the Omega signals were obliterated at about 30,000-ft altitude in a cloudy area although the aircraft was not flying through the clouds. After climbing to 35,000 ft, the reception was very good. It is suspected that ice crystals were involved. (The jet aircraft-a KC135-used no precipitation static eliminators.)

ANTENNA CHARACTERISTICS

The short vertical aircraft antennas used with the Mark I and Mark II Omega aircraft receivers were electric-field antennas with a high impedance at the base. These antennas were very susceptible to interference from precipitation static, and none of these antennas gave an acceptable performance in precipitation. Antennas tested and a brief of results are given below, further details on individual tests are given in Appendix A. The tests were performed on C54, EC121K and, KC135 aircraft.

1. Long wire antenna (EC121K). This was subject to high interference from locally generated aircraft noise and precipitation static. Performance was relatively poor even in good weather conditions.

2. Four- to 8-ft, vertical, insulated-wire antenna (C54). The antenna was subject to precipitation static and effects of water on antenna capacitance in precipitation, excellent for use in fair weather.

3. AN104 VHF Blade Antenna (EC121K, C54, and KC135). This antenna consisted of an outer metal shell around a wooden blade with a 1- to 2-in. insulating gap between the antenna and the aircraft fuselage. Even with an insulating coat of epoxy on the antenna, it was subject to shorting by precipitation as well as being extremely vulnerable to precipitation static. Reception was good in fair weather.

4. Eight-ft vertical wire in the large upper radome of the EC121K aircraft. This

antenna was not exposed to wetting but was still subject to precipitation static interference. Operation was excellent in fair weather.

5. Two-ft vertical rod antenna with entire antenna covered by 1/2- to 1-in. good insulating material (EC121K and C54). There were no effects of base shorting or change of capacitance, but the antenna was still subject to precipitation static interference; excellent in fair weather.

6. Two-ft vertical rod antenna with Teflon base insulator on belly of aircraft (EC121K). Antenna had no base shorting effects but was still subject to precipitation static interference, although there was a slight improvement in some cases. Operation was excellent in fair weather.

7. Insulated, vertical rod antenna with grounded shield on leading edge (EC121K). The shield caused considerable attenuation of Omega signals and appeared to offer little improvement in precipitation conditions; however, different shield configurations should be investigated.

The wetting effects experienced at the base of electric-field antennas in early flights were easily remedied (see Appendix A). Noise pickup on the antenna lead-in because of the high impedance of the antenna was minimized by locating an active preamplifier at the base of the antenna, but none of the electric-field antennas gave acceptable performance in precipitation. A more fundamental approach to the precipitation problem was required.

CROSSED-LOOP ANTENNA DEVELOPMENT

From elementary antenna theory it can be shown that, at a distance less than 0.01 wavelength (1000 ft at Omega frequencies) from a point-source discharge (i.e., precipitation static on the aircraft), the magnetic field produced by the discharge is considerably less than the electric field, changing relative to the electric field in direct proportion to the distance from the point source. A shielded loop antenna which utilizes the magnetic field and rejects the electric field appeared to be a reasonable approach to the reduction of precipitation effects in Omega aircraft receivers.

It was on the above basis that NRL in 1965 undertook the development of a crossed-loop antenna for Omega. The experimental antenna consisted of two orthogonal loops wound about a cubical, hollow core consisting of a number of high-permeability ferrite bars epoxied together (Fig. 2). A cage type electrostatic shield surrounded the antenna. A loop coupler was designed to switch between the orthogonal loops to select signals of maximum amplitude and positive phase in synchronism with Omega transmissions. The operation of the loop coupler initially required an automatic insertion of aircraft heading and a manual insertion of bearings to the Omega stations for operation with the Mark II receiver; however, operation of a loop coupler was further simplified and made fully automatic in the Mark III system (4) through use of the navigation computer.

NRL FLIGHT TESTS OF CROSSED-LOOP ANTENNA

In August 1966, the NRL-developed crossed-loop antenna and a 6-ft insulated-wire antenna were installed on a C54P aircraft and subjected to comparative tests under conditions of heavy precipitation during a rainstorm south of Puerto Rico.

Signals were received on both the Mark II and Omega field-strength receivers from Omega transmitters located at Trinidad, British West Indies, Haiku, Hawaii, and Forestport, New York. Outputs of the two antennas were available for continuous display and

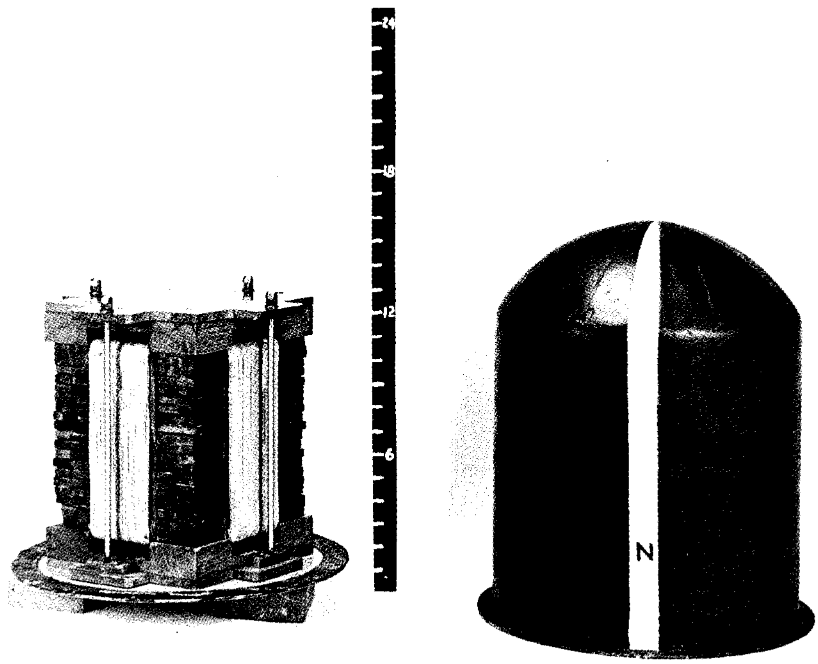

Fig. 2 - NRL crossed-loop antenna

photographing on a dual-sweep oscilloscope. Figures 3a, b, and c show outputs of the NRL field-strength receiver i-f on the ground before flight, during heavy precipitation static, and coming out of the rain, respectively. The field-strength receiver is a linear, nonlimiting receiver and provides a relatively undistorted reproduction of the actual signal from the antenna. The top trace on each photograph is the signal from the loop antenna, whereas the bottom trace is the signal from the wire antenna. Note that signal levels and local noise are the same for both antennas in Fig. 3a during fair weather conditions. In Fig. 3b, during heavy precipitation static, the Trinidad, Hawaii, and New York signals are visible on the loop-antenna trace, while the output from the wire antenna is very heavy noise. In Fig. 3c, the receiver had just begun to recover the track of the strong Trinidad signal from the wire antenna as the aircraft emerged from the rain. Signal levels on the wire were still slightly degraded due to resistive and capacitive shorting effects of water on the insulated wire antenna. Scope settings are 0.5 sec per division horizontally and 1 V per division vertically. The NRL aircraft are equipped with conventional wick static dischargers.

Figure 4 compares the Mark II receiver AGC levels for the two antennas during the same flight. The AGC level indicates the relative signal-to-noise ratio of the strong Trinidad signal during the flight. Note that during the rain, the precipitation static picked up by the wire antenna was so high as to make tracking of the Trinidad signal impossible for approximately 1 hour. However, scarcely enough precipitation interference was received by the crossed-loop antenna to even slightly degrade signal reception and tracking.

FLIGHT TESTS OF NRL MARK III

The NRL Mark III Omega Aircraft Navigation Set (4) was completed in 1968. It included a navigation computer developed under an NRL contract. The computer provided

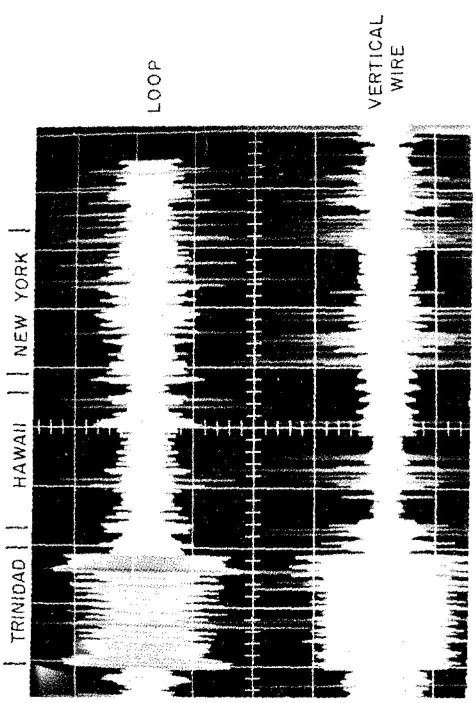

Fig. 3a - Loop and wire antenna reception in fair weather

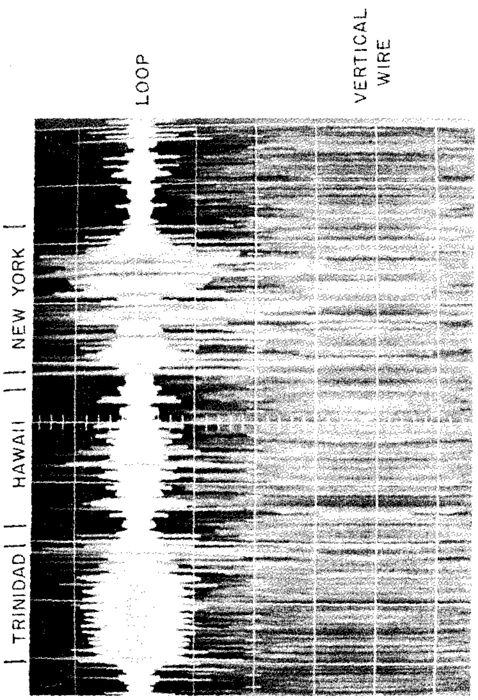

Fig. 3b - Loop and wire antenna reception in heavy rain during flight

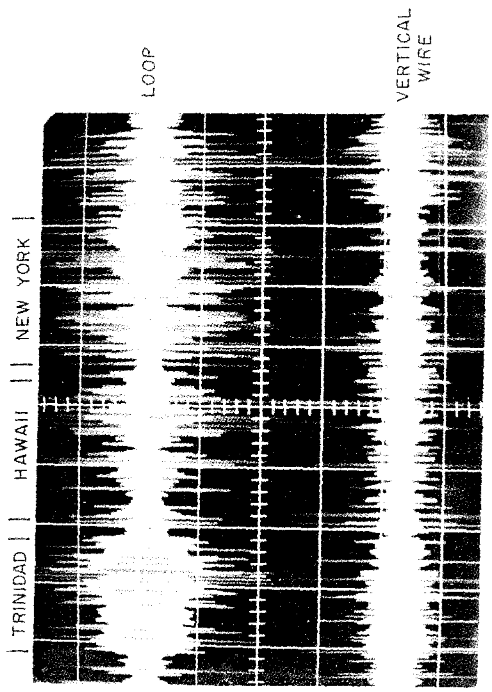

Fig. 3c - Loop and wire antenna reception immediately after rain during flight

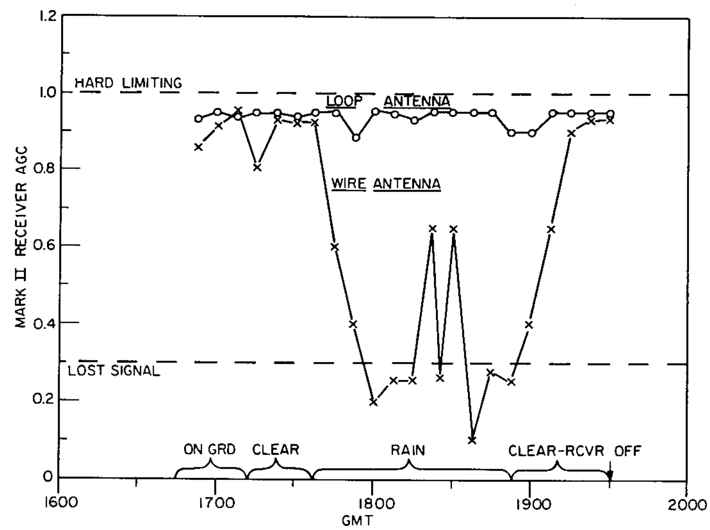

Fig. 4 - Mark II receiver AGC levels in fair weather and in precipitation (loop and vertical wire antenna)

outputs such as latitude and longitude, range and bearing to a destination, loop antenna selection signals, and cross-track error, which was coupled to a course deviation indicator in the cockpit of the NRL aircraft. The antenna used with the Mark III was a Pickard and Burns commercially produced crossed-loop antenna (Appendix A and Ref. 3), with the polyethylene-insulated rod antenna also available for use (5). The North Atlantic flight tests of the Mark III provided a dramatic evaluation of the performance of the crossed-loop antenna compared with a vertical antenna.

The North Atlantic flight tests of the Mark III were completed in October 1968 (5). The flight route was selected by representatives of the Federal Aviation Agency. It extended over 8000 mi with a proportional mixture of day, night, and transition periods to obtain information regarding the potential of Omega for civilian as well as military air use.

Two Loran C shipboard receivers were provided by the U.S. Coast Guard for comparison studies. Conventional Loran A, TACAN, VOR, ADF, and other navigational aids are standard equipment on the NRL EC121K aircraft. Omega was used as the primary navigation system on all overwater portions of the flight, with the pilots following steering directions from the Mark III-actuated Course Deviation Indicator. An antenna phasing and switching unit was installed to allow Omega operation with either the crossed-loop antenna or the 24-in., polyethylene-insulated, rod antenna without interrupting normal system operation. The Loran C equipment was provided with an 8-ft vertical whip antenna in the upper radome of the aircraft.

The flight route was from NAS Patuxent River, Maryland, to NAS Argentia, Newfoundland; Mildenhall AFB, England; Torrejon AFB, Spain; Lajes AFB, Azores; Kindley AFB, Bermuda, and back to NAS Patuxent River (Fig. 5). The flights were a complete success. Using the crossed-loop antenna, at least three Omega signals were tracked over the entire flight route. On the flight from Newfoundland to England and on the flight from Spain to the Azores, Loran A, Loran C, and communications signals were obliterated by severe rain and icing conditions for approximately 3 consecutive hours on the former and 20 min on the latter (Fig. 5). The Mark III Omega navigation set tracked consistently through both periods of precipitation static using the crossed-loop antenna (Omega signals from the polyethylene rod antenna were obliterated). This was a conspicuous illustration of the effectiveness of the crossed-loop antenna with Omega aircraft receivers and also indicated the possibilities for use of the crossed-loop with other vlf and lf navigation and communications systems.

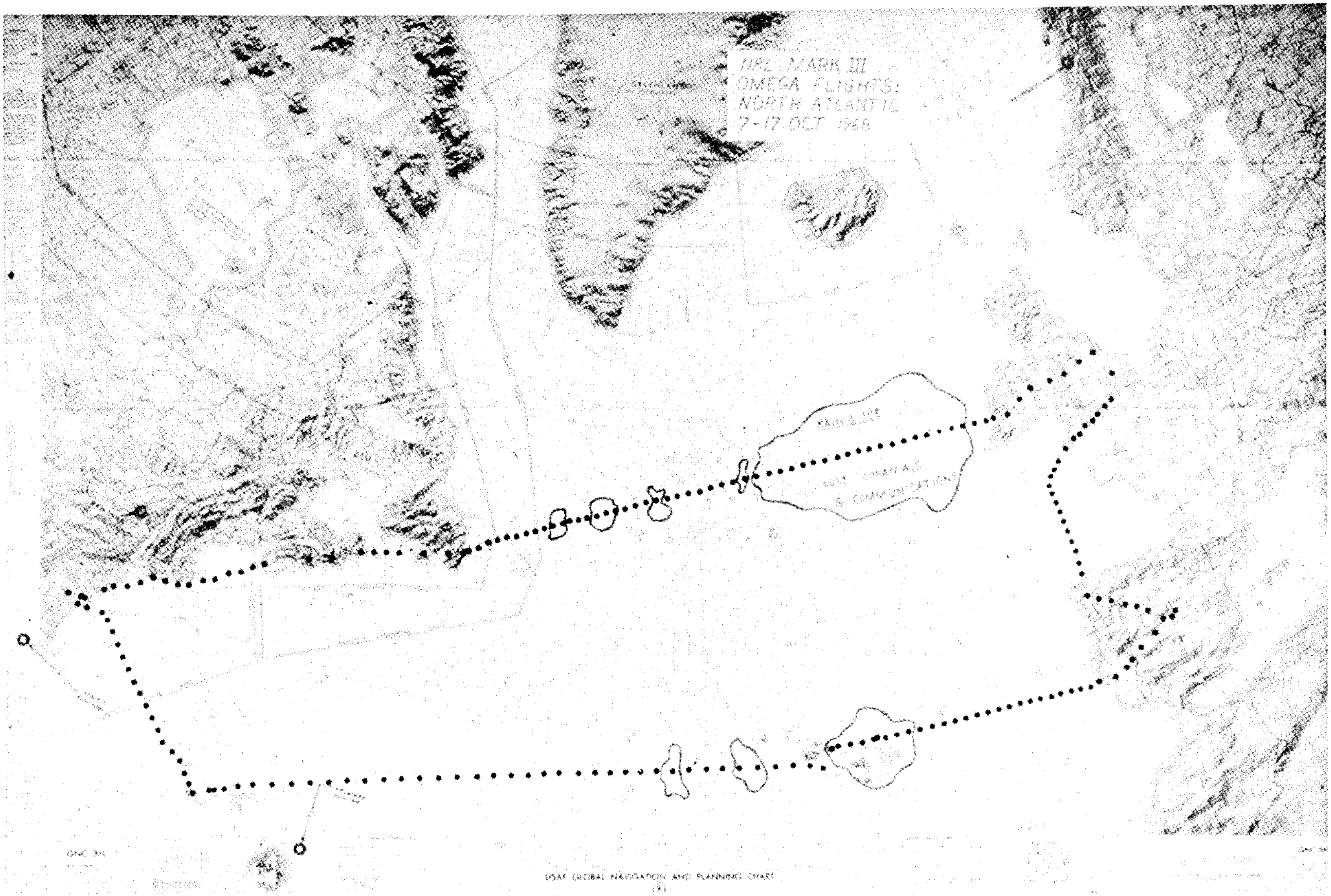

Fig. 5 - Flight path of Omega and Mark III test flights in the North Atlantic area from October 7 to 17, 1968

ANTENNA SENSITIVITY AND COMPARATIVE PERFORMANCE IN FLIGHT

Investigations of antennas in flight under precipitation conditions were accomplished to compare the performance of the Pickard and Burns commercial crossed-loop antenna with the NRL-designed blade and rod antennas. To obtain more meaningful statistical data as to antenna sensitivity and performance, a Tracor Model 7007 Omega receiver and a loop antenna were set up at NRL to continuously monitor Norway and New York Omega signal strengths. The test flights were performed within a 100-mi radius of NRL, and, since the Omega transmitters were distant, it could be assumed that the field strengths at the aircraft and at NRL were approximately equal. The receiver calibration curve and details of the methods used to calibrate the receiver are given in Appendix B.

A local flight test was performed on April 16, 1968 to compare the crossed-loop with the rod antenna on the belly of the aircraft in normal weather conditions. Atmospheric and local noise was about 30 μV/m in a 60-Hz bandwidth measured at the aircraft during most of the flight period. Signal levels from Norway were 6-13 μV/m during the flight test, and the NRL Mark II Omega receiver tracked the Norway signal with approximately equal performance from both antennas.

During a night flight on April 24, 1968, in precipitation with the loop and insulated rod antenna in time-shared operation, the effects noted were similar to those encountered with the NRL loop and long wire antennas in Puerto Rico. Figure 6 shows the loop and insulated-rod outputs compared on the NRL field-strength receiver i-f in fair weather early in the flight. Note that signal levels and local noise are about the same for both antennas. Figure 7 shows the same outputs compared during heavy precipitation. The Mark II tracked the Norway signal in the precipitation at signal strengths of 10 μV/m with the crossed-loop antenna, while with the insulated rod antenna the receiver could not track Norway at signal strengths of 18 μV/m and higher during the precipitation.

On flights from Andrews AFB, Maryland, to Homestead AFB, Florida, and return on May 22-23, 1968, during a low atmospheric noise period, the Norway signal from the crossed-loop antenna was tracked during the entire 10 hours of flying time. Signal strengths of the Norway signal during the flight period were measured at 7 to 10 μV/m.

A flight to compare the dual-mounted shielded and unshielded insulated-rod antennas, the crossed-loop antenna, and the rod antenna on the belly of the aircraft was accomplished on May 28, 1968. The flight was primarily in heavy electrical storm areas with an extremely high level of far-field electromagnetic noise received by all the antennas. Relative noise measurements made with the NRL Omega field strength receiver are shown in Table 1, and pictures comparing the outputs of the antennas on the NRL Omega field strength receiver i-f are shown in Figs. 8 and 9. (Note the low signal level on the shielded antenna due to attenuation by the shield.) The existence of weather conditions of this type emphasizes the need for higher-powered Omega stations. During the high noise periods, the Norway signal was unusable and the Hawaii signal was marginal for tracking with both the crossed-loop and blade antennas.

In Table 1, the effective heights of the four antennas are normalized with respect to one another, and the equivalent noise in a 1-Hz bandwidth at the antenna terminals is calculated from relative noise readings on the NRL Omega field strength receiver under the various weather conditions encountered in the flight. The noise increased proportionately on all antennas as the storm became more severe. However, the relative noise level on the loop was considerably lower than that on the other antennas.

Additional work initiated at NRL included an evaluation of semiconductive coatings for electric-field antennas and improvements in shielding. However, further evaluation of antennas was discontinued due to the high priority of the NRL Mark III Aircraft Omega

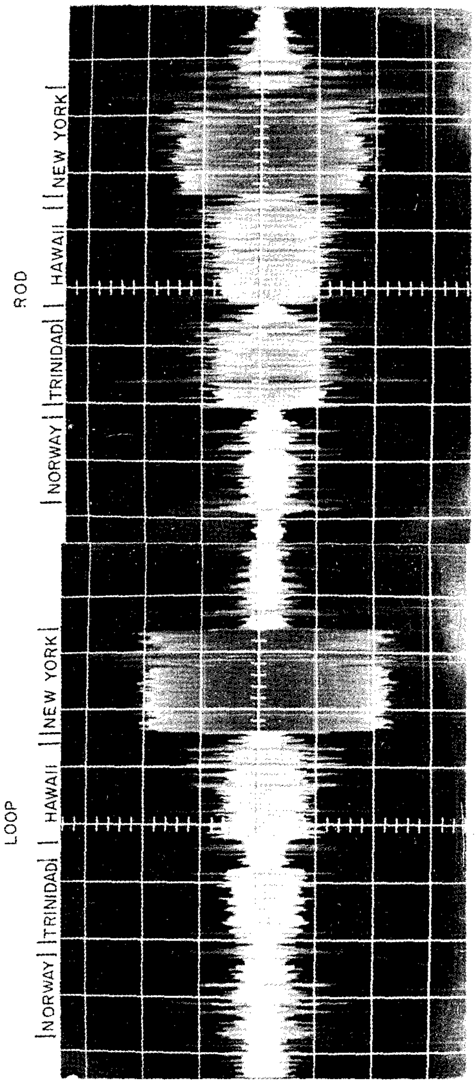

Fig. 6 - Outputs of loop and insulated rod antennas in fair weather

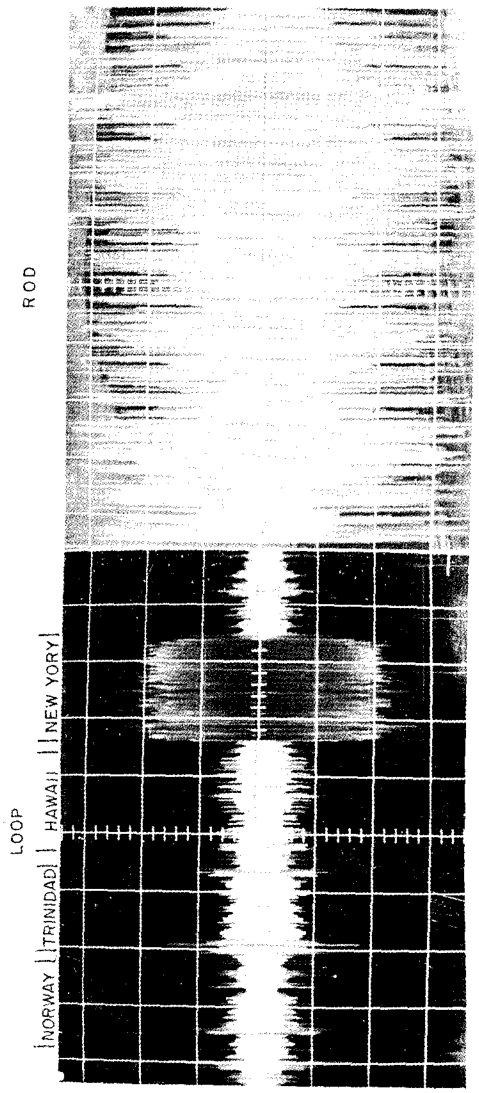

Fig. 7 - Outputs of loop and insulated rod antennas in precipitation

Table 1
Normalized Noise Levels at Antenna Terminals during a Severe Electrical Storm on May 28, 1968

Antenna Type	Effective Noise (μV) vs Storm Severity*		
	Light	Moderate	Severe
Crossed Loop	15	35	65
Blade	35	60	90
Shielded Blade	45	-	180
Rod	50	105	170

*Noise levels normalized to a 1-Hz bandwidth

Receiver flight tests and, later, a reduction of project funds. Additional work on antenna studies was performed by Pickard and Burns Electronics under Navy, FAA, and company sponsorship (6-8). The flight evaluation by NRL of new antennas developed under this program was terminated.

CONCLUSIONS AND RECOMMENDATIONS

The crossed-loop antenna appears to be the only presently available solution to the effects of precipitation static on Omega aircraft receivers. However, the investigation of other possible solutions to the problem should be continued. All possible combinations of static dischargers, aircraft bonding practices, and antenna shielding have not been completely investigated; investigations along these lines should be continued.

Proper location of the crossed-loop antenna on the aircraft is essential in order to avoid interference from ground return currents in the aircraft (Appendix A). Additional circuitry is required for the automatic switching and phasing of the crossed-loop outputs, although this is minimal in an Omega receiver-computer package. A possible advantage of the crossed-loop antenna, aside from its use in precipitation environments, is that it may be flush-mounted for high-performance aircraft (7). Until future research reveals other possible solutions to precipitation interference, the crossed-loop antenna will be an essential component of an all-weather Omega aircraft receiver system.

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The author also wishes to thank the NRL Operational Services Office and the flight crews of the NRL C54P and EC121K aircraft for scheduling the aircraft and accomplishing the flights under adverse weather conditions.

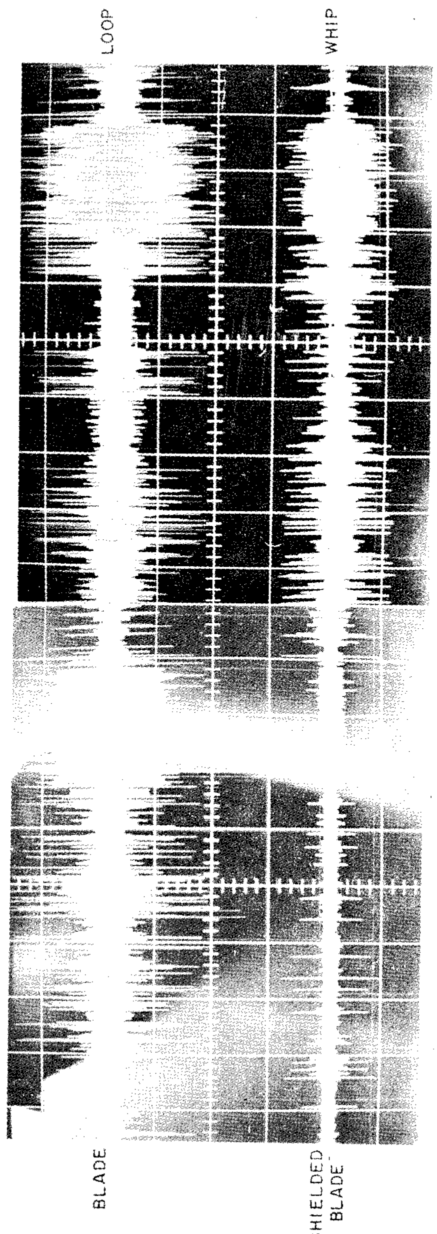

Fig. 8 - Antenna outputs in fair weather: loop, whip, blade, and shielded blade

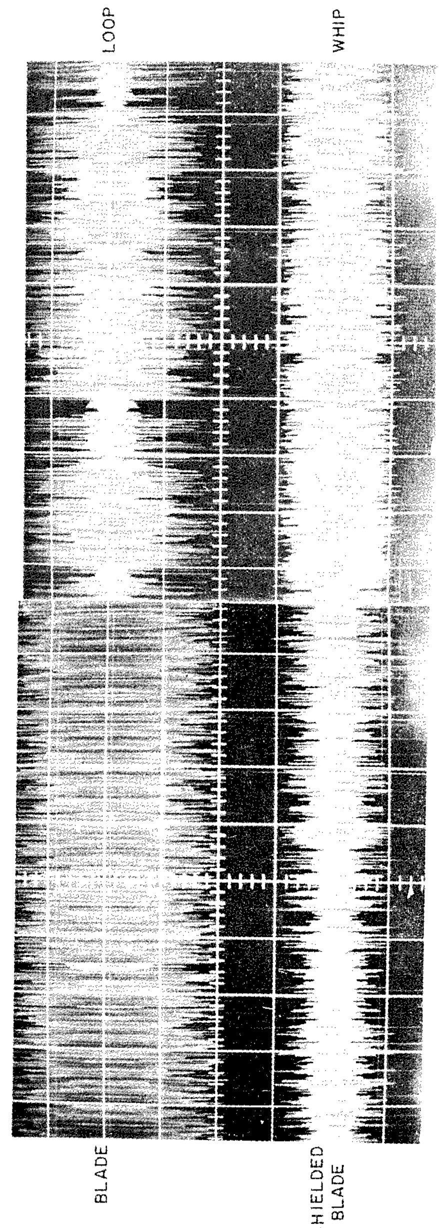

Fig. 9 - Antenna outputs in severe electrical storm: loop, whip, blade, and shielded blade

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Appendix A

INITIAL ANTENNA INVESTIGATIONS

THE NRL POLYETHYLENE-INSULATED ROD ANTENNA

In order to eliminate the antenna base shorting and detuning effects experienced in precipitation with earlier vertical antennas, NRL developed a polyethylene-insulated, vertical, rod antenna (Fig. A1). Antenna characteristics are listed in Table A1. Pictures were taken of the NRL Omega field-strength receiver i-f with the insulated rod in use during a local test flight in the Washington, D.C., area on October 5-6, 1967 in a C54P aircraft. Figure A2a shows the NRL Omega field-strength receiver i-f while in flight in fair weather. The noise is quite low, and the Trinidad, Hawaii, and New York signals are visible on the oscilloscope trace. Figure A2b shows the field-strength receiver i-f during a short period of rain. Note the high noise level due to precipitation interference. The Mark II Omega receiver lost track of the Hawaii signal for 5 min during this period, but rate-aiding carried the signal channel in the receiver without lane loss. Figure A2c shows the signals as the aircraft emerged from the rain. Note that the signal levels (compare the New York signal levels in Figs. A2a and A2c) were not reduced by shorting and detuning effects, as was experienced with previous antennas. However, as expected, the effects of noise due to precipitation were still too extreme for adequate tracking of Omega signals for prolonged periods without lane loss.

THE NRL SHIELDED INSULATED ROD ANTENNA

The effects of discharges occurring during precipitation on insulating surfaces such as exterior surfaces of antennas is well described in Refs. A1-A3. Shielding of the antenna with either a grounded metal leading edge or a semiconductive coating appeared to be a possible solution to noise generated by these discharges.

In order to check these antenna shielding principles, NRL constructed a dual antenna mount using two modified AN-104AX antennas (Fig. A3). The outer metal covers were removed from the wooden bodies, an insulating coat of epoxy applied, and a metal rod inserted in the center of the mast to eliminate the insulator shorting effect. On one of these antennas a grounded metal shield covered the leading edge of the antenna. Antenna details and characteristics are given in Table A1.

Further tests indicated that the shielded rod antenna did not have satisfactory sensitivity for operation with the Mark II antenna preamplifier, due to attenuation caused by the shield. The metal rod was then moved to the back of the wooden blade, further away from the shield, and somewhat better sensitivity was obtained. Tests to indicate directivity of the antenna and effective height relative to the unshielded rod were made utilizing off-the-air signals and the NRL field-strength receiver.

Table A2 indicates the results of these tests. The antennas were rotated at 22-1/2-degree intervals, and relative amplitudes of the off-the-air signals were measured from the antennas. Antenna preamplifiers were then interchanged between the antennas to assure an equitable test. The results indicate that the antenna pattern of the shielded rod was omnidirectional (no nulls introduced by the shield), but that the shield introduced

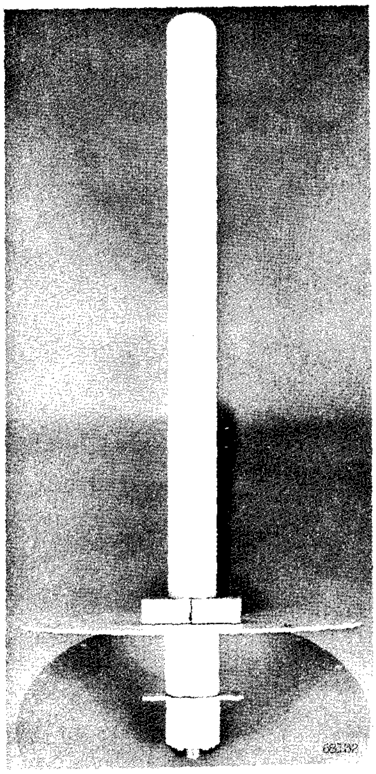

Fig. A1 - NRL polyethylene-insulated rod antenna

about 10 dB of attenuation to off-the-air signals. Further design changes might have reduced the attenuation caused by the shield. However, this antenna was considered satisfactory for evaluating relative performance under precipitation conditions, although it was not adequately sensitive for operational use.

LOWER ROD ANTENNA CONCEPTS

One of the questions raised by the performance of the insulated rod antenna on the C54P aircraft was whether arcing of static charges built up on the insulation surrounding the antenna itself was actually causing the noise problems encountered in precipitation conditions. The antenna shown in Fig. A4 was developed to eliminate the possibility of wetting and of static discharges occurring due to particles striking the insulation surrounding the antenna. Note that the antenna itself is uninsulated except for the Teflon base insulator. The antenna was also located below the belly of an NRL EC121K aircraft and behind the lower radome in order to reduce the probability of wetting the base insulator during precipitation (Fig. A5).

INSTALLATION PROBLEMS OF CROSSED-LOOP ANTENNA

The commercial crossed-loop antenna still appeared to be the best solution to the problems of precipitation effects; however, previous investigations were hampered by locally generated aircraft electrical noise which interfered with the loop antenna installation. Therefore, it became necessary to isolate and eliminate the electrical noise problems before a satisfactory evaluation of the crossed-loop antenna could take place.

In October 1967, the commercial crossed-loop antenna (Fig. A5) was installed on an NRL EC121K aircraft. A solid-state crossed-loop preamplifier was acquired from

Table A1
Antenna Wetting Tests
June 21, 1967 to August 8, 1967

Antenna	Antenna and Cable C (pF)	Antenna and Cable D*	Cable C (pF)	Cable D	Dry or Wet	Test Frequency f (kHz)	Antenna C (pF)	Antenna Capacitive Reactance at 10 kHz† (MΩ)	Antenna Resistance to Ground‡ (MΩ)
AN104	229.0	0.00330	189.4	0.00030	Dry	10.0	40	0.397	22.8
AN104	229.0	0.0700	189.4	0.00030	Wet	10.0	40	0.397	0.995
Polyethylene Insulated Rod	216.0	0.00040	189.4	0.00030	Dry	10.0	27	0.590	526
Polyethylene Insulated Rod	216.3	0.00100	189.4	0.00030	Wet	10.0	27	0.590	99.5
Lucite Insulated Rod	214.0	0.00030	189.4	0.00030	Dry	10.0	25	0.638	2010
Lucite Insulated Rod	215.0	0.00240	189.4	0.00030	Wet	10.0	26	0.614	34.6
Rod in AN104 Shell (Dual Mount)	158.0	0.00451	137.5	0.00000	Dry	10.0	21	0.760	21.2
Rod in AN104 Shell (Dual Mount)	159.0	0.01500	137.5	0.00000	Wet	10.0	22	0.725	6.68
Rod in AN104 Shell With Front Shield (Dual Mount)	172.0	0.00720	137.5	0.00000	Dry	10.0	35	0.456	12.9
Rod in AN104 Shell With Front Shield (Dual Mount)	173.0	0.01300	137.5	0.00000	Wet	10.0	36	0.443	7.06
B57 Blade	226.0	0.00200	189.4	0.00030	Dry	10.0	37	0.418	38.6
B57 Blade	394.0	0.5200	189.4	0.00030	Wet	10.0	205	0.0794	0.0776

*D = Dissipation Factor = 1/Q

†Antenna capacitive reactance = $[2\pi f\,(C_{antenna})]^{-1}$

‡Antenna resistance to ground = $[2\pi f(D_{antenna\ and\ cable})(C_{antenna\ and\ cable}) - 2\pi f(D_{cable})(C_{cable})]^{-1}$

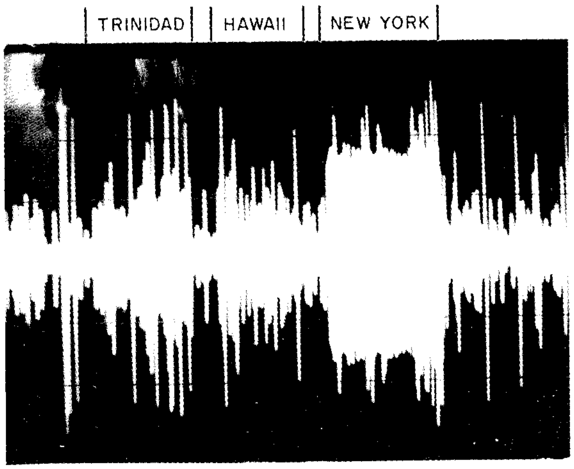

Fig. A2a - Polyethylene insulated rod antenna output in fair weather

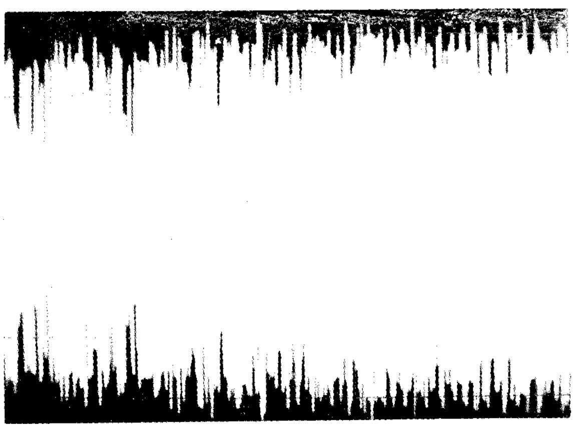

Fig. A2b - Polyethylene insulated rod antenna output in precipitation

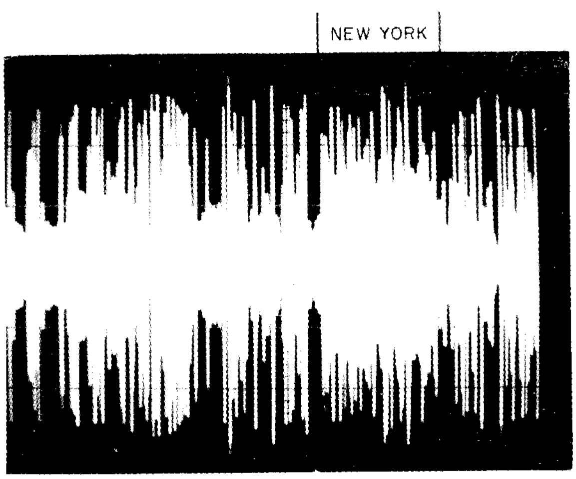

Fig. A2c - Polyethylene insulated rod antenna output while emerging from precipitation

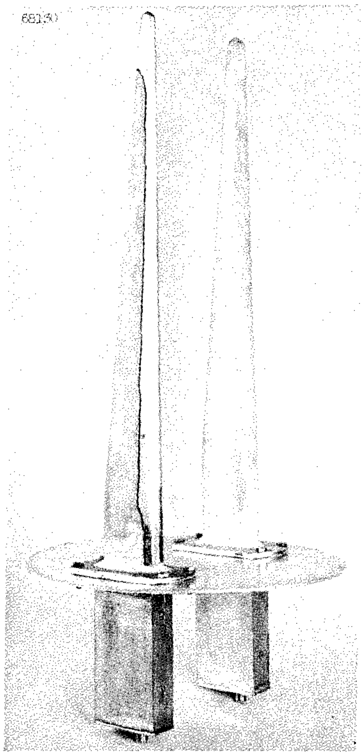

Fig. A3 - Dual-mounted shielded and unshielded insulated rod antenna

Pickard and Burns, and additional hardware was designed and developed at NRL for coupling the antenna with existing components of the Mark II Omega receiver. The results of sensitivity measurements of the overall loop system taken in a shielded room at NRL agreed closely with the sensitivity claimed by the manufacturer. The tests indicated adequate sensitivity for reception of Omega signals, provided local noise sources could be adequately suppressed or isolated on the aircraft.

In order to find the best possible location for the crossed-loop antenna consistent with aircraft structure and low radiated magnetic noise, the NRL EC121K aircraft was placed in an electrically shielded hangar at the Naval Air Test Center, Patuxent River, Maryland. The aircraft electronics and power systems were operated on the ground, and measurements of relative radiated magnetic noise were taken near the fuselage of the aircraft at possible locations for mounting the crossed-loop antenna. The measurements were made with a small Stoddart loop antenna and vest-pocket vlf receiver with a diode detector and microammeter connected to the audio output. The best location (lowest noise pickup) for the crossed-loop antenna was found to be aft of the cargo door, on the belly of the aircraft (Fig. A5). This proved to be an excellent location, since the crossed-loop antenna was located near the whip antenna with which it was compared during flight tests.

The solid-state crossed-loop preamplifier was designed to utilize up to 50 ft of cable between the antenna and the preamplifier. The long input cable was found to be unsatisfactory on the NRL aircraft under all possible grounding configurations of the cable shield due to noise pickup in the cable. It became necessary to locate the preamplifier as close to the loop as practical and use much shorter input cables (2 ft). This procedure is recommended, since several nanovolts of noise (in the Omega frequency range) at the crossed-loop preamplifier input terminals would seriously affect system performance due to the extremely low effective heights of the loops (less than 1 mm) and high voltage gain of the preamplifiers (64 dB).

Table A2
Shielded Antenna Pattern Tests, February 6, 1968

Shield Heading (deg)	Unshielded Antenna Signal Strength (μV)			Shielded Antenna Signal Strength (μV)		
	Trinidad	Hawaii	New York	Trinidad	Hawaii	New York
0	36	12	195	12	4	65
22.5	37	12	165	11	4	60
45	35	12	165	11	3	60
67.5	36	12	185	12	4	60
90	35	11	180	11	3	60
112.5	35	12	180	11	4	60
135	36	12	185	11	4	60
157.5	37	11	185	11	4	60
180	37	12	190	11	4	60
202.5	37	13	185	11	4	60
225	38	14	190	12	4	60
247.5	38	14	190	11	4	60
270	37	13	200	11	4	65
292.5	37	13	190	11	4	65
315	37	14	195	12	4	65
337.5	35	13	190	12	4	65
360	36	12	180	12	4	65

During early checkout flights in March 1968, it was discovered that, although the crossed-loop antenna appeared as sensitive as any of the Omega vertical antennas while the aircraft was on the ground and being taxied, the antenna received extremely high-level interference just before aircraft takeoff, during initial climb, and also during approach. The antenna also received moderate interference when the aircraft cabin air recirculating fans were in operation. The cause of the extreme noise during takeoff and landing was isolated to the auxiliary hydraulic boost pump dc motors in the tail of the aircraft. The "auxiliary boost" is only used during takeoff and approach to supplement aircraft power to the hydraulic system.

It was found that the Naval Oceanographic Office's Project Magnet had experienced similar noise interference to magnetic sensors on the same type of aircraft. Consultations with Project Magnet personnel revealed that noise from the +28-v dc ground-return paths through the aircraft skin and framing, particularly from rotating machinery drawing heavy dc current, caused magnetic-field interference (Fig. A6). Their solution to the problem was to rewire all dc machinery and lighting to a two-wire, twisted-pair system with the ground wires all returned to a central bus. The problems involved in the NRL aircraft were not corrected, since the "auxiliary boost" is, in general, not in operation long enough to cause loss of Omega lanes and is only used during takeoff and approach, and the recirculating fans can be turned off during periods when higher sensitivity is

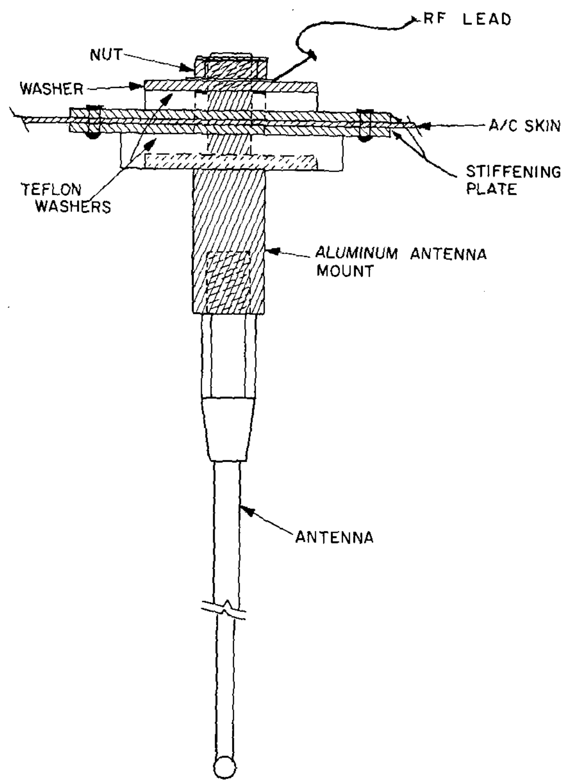

Fig. A4 - Aircraft whip antenna

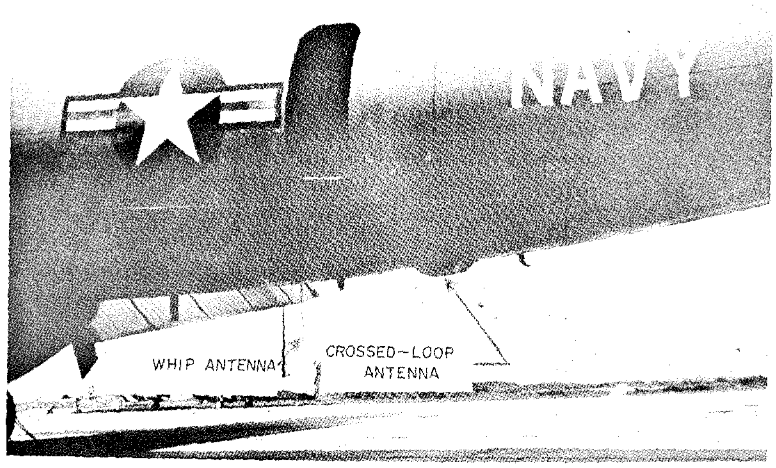

Fig. A5 - Whip and crossed-loop antennas mounted on aircraft

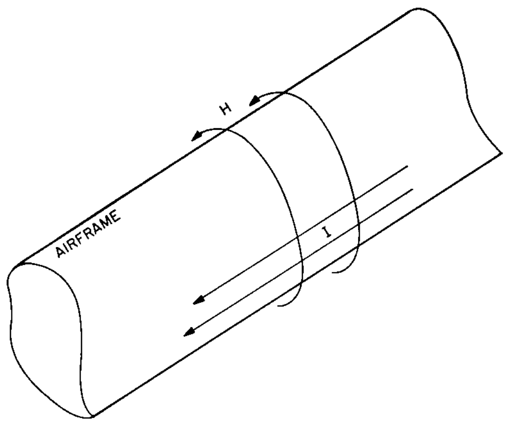

Fig. A6 - Magnetic noise field (H) caused by a ground return (I) in the airframe

required due to weak Omega signals. No other dc circuitry and none of the ac machinery and equipment on board the NRL aircraft caused any appreciable rf noise.

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Appendix B

OMEGA FIELD-STRENGTH MEASUREMENTS

The Tracor Omega receiver was calibrated as follows: An AN/URM-41 field-strength receiver was used to measure New York absolute signal strength. New York relative signal strength (dB) was simultaneously recorded by the Tracor receiver. The Tracor receiver was calibrated using a GR-1162A frequency synthesizer and an HP 302A wave analyzer to determine relative field strength (Tracor receiver output) vs absolute input voltage (V_{in}) at the receiver input terminals for each of the four receiver channels. The effective height of the Tracor loop antenna (H_e) could then be calculated as

$$H_e = \frac{V_{in}}{E_{abs}},$$

where E_{abs} was the absolute field strength of the New York Omega signal in microvolts per meter as measured with the URM-41 field-strength meter, and V_{in} was the signal level in microvolts at the input to the Tracor receiver corresponding to the relative amplitude of the New York signal recorded by the Tracor receiver (Fig. B1). The effective height of the antenna H_e was calculated as 2.35 mm. Using one channel of the Tracor

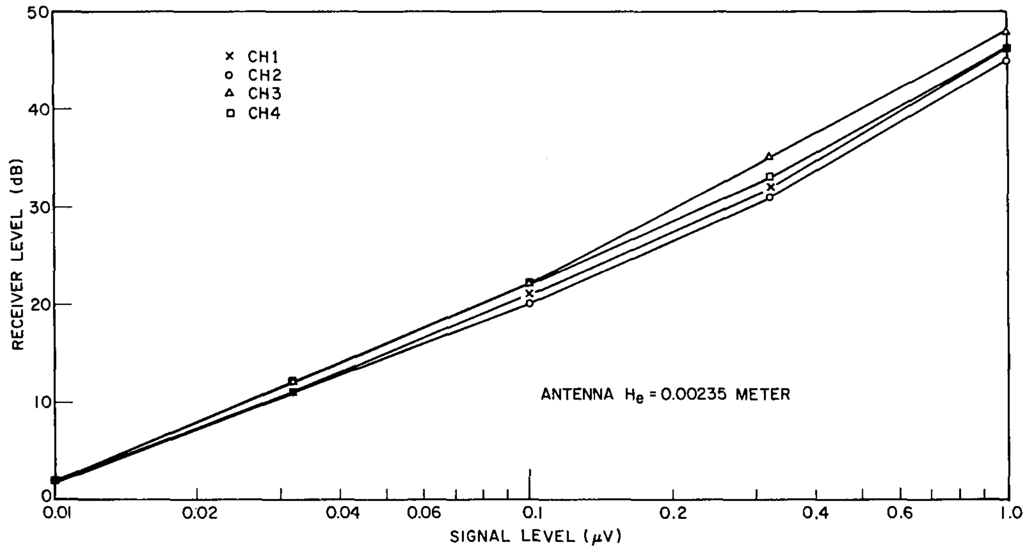

Fig. B1 - Tracor Receiver Model 7007 calibration curve receiver to measure atmospheric noise in an unused Omega segment, the absolute field strength of any Omega signal could now be determined by the equation

$$E_{abs} = \sqrt{(V_{in})^2 - (V_n)^2} \Big/ H_e,$$

where V_{in} was the absolute signal voltage at the input to the receiver, and V_n was the absolute noise voltage at the antenna terminals of the receiver (Fig. B1). Due to the limited performance of the ground monitor equipment and the very low signal strength of Norway, only a fair degree of accuracy could be expected on the Norway field-strength measurements (perhaps ±50%). The NRL Omega field-strength receiver on the aircraft provided a comparative check of relative field strengths measured at the NRL monitor.