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Radar Detection of Surface Oil Slicks

Real- and synthetic-aperture radars were compared with regard to the detection of surface oil slicks and other marine targets.

Abstract: *The United States Coast Guard currently is developing AIREYE, an all-weather, day/night airborne surveillance system, for installation aboard future medium range surveillance (MRS) aircraft. As part of this program, a series of controlled tests was conducted off southern California during May, 1976 in order to evaluate the oil slick and surface target detection capabilities of two Motorola-developed side-looking radars. The systems, a real-aperture AN/APS-94D and a synthetic-aperture coherent-on-receive (COR), were flown over the Santa Barbara Channel on May 19, 1976. Targets imaged during the coincident overflights included natural oil seepage, simulated oil spills, oil production platforms, piers, mooring buoys, commercial boats and barges, small pleasure craft, and coastal kelp beds. This paper describes the test program and compares oil and surface target detection results for the two systems. Based on an analysis of imagery from the coincident radar runs, COR provided better detection of natural and man-made oil slicks, whereas the AN/APS-94D consistently exhibited higher surface target detection results.*

Introduction

From May 19 to May 21, 1976 the United States Coast Guard sponsored limited tests of two side-looking airborne radar (SLAR) systems off the coasts of southern and central California. The principal objective of the test program was to document and compare overwater performance capabilities of real- and synthetic-aperture radars against a range of man-made and natural surface targets. As an integral part of performance documentation, the Geography Remote Sensing Unit, University of California, Santa Barbara provided sea-truth data support and an assessment of the relative detection capabilities of the two systems. Systems involved in the test program were an X-band horizontally polarized AN/APS-94D real-aperture radar and an X-band vertically polarized coherent-on-receive (COR) synthetic aperture system. Both radars were designed and developed at Motorola's Government Electronics Division, Scottsdale, Arizona.

At the time of the tests the two systems

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were potential candidates for inclusion in the Coast Guard's AIREYE sensor package. AIREYE is an all-weather, day/night wide-area airborne remote sensing system being developed for operational use aboard the Coast Guard's medium range surveillance (MRS) aircraft. Sensor selection for AIREYE was the direct result of evaluation tests involving the Coast Guard's earlier airborne oil surveillance system (AOSS). Background information on the AOSS program and full particulars on sensor evaluations appear in the 1973 and 1975 Conference on Prevention and Control of Oil Pollution Proceedings and in a final report from Aerojet Electro-Systems Company to the Coast Guard (Ketchel and Edgerton, 1973; Maurer and Edgerton, 1975; Edgerton *et al.*, 1975). The AIREYE sensor package will include a side-looking airborne radar (SLAR), infrared/ultraviolet line scanner (IR/UV-LS), aerial reconnaissance camera (ARC), active-gated television (AGTV), and an airborne data annotation system (ADAS). Initially, the Coast Guard plans to equip six MRS aircraft with the full AIREYE sensor package.

The test program reported here is unique in that it represents one of the few documented comparative evaluations of real- and synthetic-aperture SLAR systems and to our knowledge, the first time that two such systems have been flown coincidentally to image oil pollution and other sea surface targets. Also, the tests presented an opportunity to compare the relative overwater performance capabilities of horizontally and vertically polarized antennas. Although our evaluation of the imagery from the test program covered a wide range of natural and man-made targets, this paper will emphasize our comparative assessment of the oil pollution detection capabilities of the two radar systems.

Radar Systems

AN/APS-94D

The AN/APS-94D system was installed aboard a Grumman OV-1D with a 16-foot-long horizontally polarized antenna. Like most real-aperture radars, the AN/APS-94D antenna has a very narrow dimension in the horizontal direction and wide-angle coverage in the vertical. Consequently, a long narrow strip of the Earth's surface is illuminated from beneath the carrier aircraft to some maximum range. The antenna is fed with a pulse of EMR which moves at the speed of light within the beam and illuminates points along the flight line. Returns scattered back from targets at different angles are temporally separated at the radar receiver. A synchronized intensity-modulated light spot scans a line across photographic film and records target returns at their scaled slant range distance. After each line of video return is recorded, another pulse is transmitted in order to obtain a new scan. The film speed is proportional to the aircraft speed over the ground (Motorola, Inc., 1975).

The azimuth resolution of the AN/APS-94D is diffraction-limited and dependent on real antenna length. At a given range, azimuth resolution will be approximately equal to the dimensional width of the radar beam (half-power points at the range). Range resolution is dependent on transmitter pulse length. The theoretical range resolution is specified as half the pulse length. Maximum range resolution of the AN/APS-94D is approximately 30 meters with a range setting of 25 to 50 km. With the radar switched to a maximum range of 100 km, range resolution is approximately 60 meters. As a result, real-aperture systems are often restricted to relatively short-range operations and the use of short wavelengths when fine resolution is required (Motorola, Inc., 1975; Reeves, 1975).

COR

The synthetic-aperture COR system was mounted on board a U.S. Army C-47 transport with an 8-foot vertically polarized antenna. Basically, synthetic-aperture systems simulate the performance of an antenna that is much longer in the direction of flight than the actual physical antenna employed. This results in improved azimuth resolution beyond that available from the theoretical beam width of the antenna. Although the physical antenna associated with the COR system scans the terrain in the same manner as the AN/APS-94D antenna, the phase and amplitude of returns from signals transmitted at intervals along the flight path are measured and stored rather than being recorded at near-real time on strip imagery. After the physical antenna has traversed a specific distance, the stored signals can be combined to produce a return similar to that obtained from a "real" antenna having the same physical length. Furthermore, it is possible to focus at each range separately by proper adjustment of the phases of the returned signals before they are summed. Thus, azimuth and range resolutions for COR are not as dependent on physical antenna size or on pulse length (Fraser and Morris, 1976). The COR system used for these tests was modified at Coast Guard request to have the capability to detect fixed and moving targets. This was accomplished by changing the filter frequencies so that every other pulse period was discarded.

Flight Test Program

Originally, coincident radar imagery overflights of three coastal California offshore areas were planned. However, once flight operations began, aircraft maintenance and scheduling problems made this goal unattainable. Concurrent imagery was acquired on only one date, May 19, 1976, over the western Santa Barbara Channel (Figure 1a). During this flight a wide range of fixed and moving targets as well as oil pollution from natural and man-induced sources were imaged. On May 20, the flight test area was shifted to the Ventura-Oxnard-Port Hueneme offshore area (Figure 1b), where the AN/APS-94D equipped OV-1D completed runs over the eastern Santa Barbara Channel. On the following day, flight operations were moved approximately 150 miles northwest to Morro Bay (Figure 1c) where the COR aircraft imaged targets similar to those encountered in the Santa Barbara Channel.

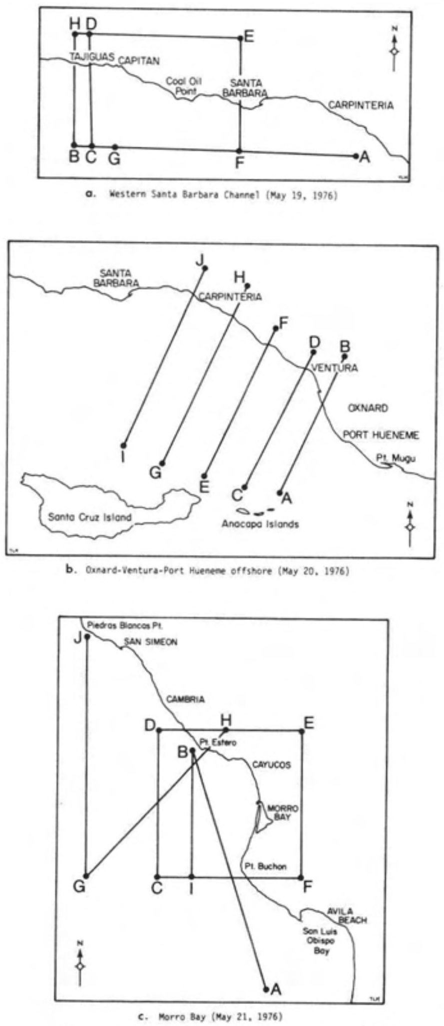

Fig. 1. Approximate flight tracks flown by sensor aircraft during the May 19-21, 1976 radar tests.

Participants in the flight test program included personnel from the U.S. Coast Guard; U.S. Army; Government Electronics Division of Motorola, Inc.; U.S. Naval Research Laboratory (NRL); and the Geography Remote Sensing Unit (GRSU), University of California, Santa Barbara. The Coast Guard was responsible for providing overall project coordination and ship support in each of the test areas. The Army supplied the OV-1D and C-47 sensor aircraft and flight crews. Motorola engineers flew with the C-47 and were charged with operating and maintaining the COR system. Investigators from NRL created simulated oil slicks off Santa Barbara and Morro Bay by using oleyl alcohol dispensed from Coast Guard vessels. Researchers from GRSU conducted "sea-truth" data verification flights over each test area, coincident with AN/APS-94D and COR overflights, and in-depth interpretation and analysis of the radar imagery.

Sea-Truth Support and Image Interpretation Activities

Major objectives of the sea-truth support activities conducted coincident with the AN/APS-94D and COR overflight were to identify radar targets in each of the test areas and accurately record their locations. Sea-truth data formats included low-altitude aerial photography, detailed sketch maps, and field notes. A Cessna 172 served as the airborne observation platform. All sea-truth/target identification flights were coordinated with a Coast Guard field project officer. Continuous radio contact was maintained between sea-truth and radar imagery acquisition aircraft during flight operations. This permitted real-time dissemination of information concerning surface targets, and facilitated the movement of the light aircraft to targets of opportunity.

Two experienced photographers and a qualified observer were present on each sea-truth flight. Photographic equipment included 35 mm cameras fitted with Kodak Wratten 1A (haze) and/or Kodak Wratten 15 (medium yellow) filters. Twenty-eight mm wide-angle and 135 mm telephoto lenses also were used. Film types included conventional color (Kodachrome 25), infrared Ektachrome (IE-135), and black-and-white (Panatomic X). The flight observer was responsible for maintaining radio communication with the field project officer, taking detailed notes, drawing sketch maps for locating moving and stationary targets, and keeping camera logs. Marginal visibility over the three flight test areas somewhat reduced the quality of sea-truth imagery. Despite this problem, all potential radar targets visually sighted by the sea-truth verification team were successfully photographed.

Following completion of the flight test program, field notes and sketch maps were finalized and all film was processed. Color and color-infrared slides were sorted and annotated with information from the camera logs. The location of fixed, moving, and surface pollution radar targets was recorded on preliminary planimetric base maps of each overflight area.

Upon receipt of the radar imagery, an evaluation of the target detection capabilities of the two systems was initiated. A total of 17 AN/APS-94D and 20 COR radar images was analyzed. In order to facilitate interpretation, images were arranged sequentially by radar system, overflight date, and flight run number. Radar images for each run were interpreted by individuals who had participated in the sea-truth data collection program and were familiar with the location of the major targets of interest in the test areas. In order to determine target detectability/non-detectability and resolution characteristics of the AN/APS-94D and COR, the following procedures were used when evaluating individual flight runs:

- Ground-truth data and target location maps were reviewed to determine the locations of all known targets in the imaged area;
- Known targets identified on the imagery by interpretation were recorded as *detected*;
- Interpreted marine and nearshore targets were annotated on frosted acetate overlays;
- Comprehensive target data, including target type, slant range distance from the aircraft, location, material composition, and whether detected or not detected, were compiled for each run; and
- Individual target returns were evaluated for interpretability and ranked on a scale from poor to good based on qualitative criteria.

Results

Following are results of our evaluation of the target detection capabilities and image interpretability characteristics of the AN/APS-94D and COR systems. These determinations were based on analysis of imagery from ten coincident AN/APS-94D and COR flight runs over the western Santa Barbara Channel, seven AN/APS-94D radar runs off Ventura-Oxnard-Port Hueneme, and ten COR runs in the Morro Bay area (Estes and Kraus, 1976).

Target Detection

Summary results of the target detection performance of AN/APS-94D and COR for known targets in the three overflight areas are presented in Table 1.

Man-Made Targets. AN/APS-94D achieved the highest detection rate for man-made surface targets, imaging 95.7 percent of the possible targets (156 of 163) during the May 19 test, and 96.9 percent (93 of 96) on May 20. COR was less consistent, detecting 94.9 percent of known man-made targets (169 to 178) on May 21, but only 74.7 percent (121 of 162) on May 19 when flown coincident with the AN/APS-94D. Based on analysis of data for the coincident overflights of May 19, AN/APS-94D exhibited the highest overall target detection rate, imaging 83.1 percent of the known man-made and natural targets

Table 1. Detection/Non-Detection of Known Offshore Targets by AN/APS-94D and COR Radar Systems

		Man-Made Targets[A]			Surface Slick Targets[B]			All Targets		
System	Date	Possible[C]	Detected	%	Possible	Detected	%	Possible	Detected	%
AN/APS-94D	5/19	163	156	95.7	38	11	28.9	201	167	83.1
COR	5/19	162	121	74.7	38	25	65.8	200	146	73.0
AN/APS-94D	5/20	96	93	96.9	0	0	....	96	93	96.9
COR	5/21	178	169	94.9	2	0	0.0	180	169	93.9

[A] Buoys, floats, and moorings; piers, pilings, rock groins, and breakwaters; platforms and vessels.
[B] Natural oil seeps and oleyl alcohol spills.
[C] Derived by summing all known targets in each image overflight area. AN/APS-94D and COR totals for 5/19 do not agree due to slight variations in radar run flight tracks and areas imaged.

(167 of 201) compared to COR's detection rate of 73.0 percent (146 of 200).

A *t*-test was performed on the May 19 Santa Barbara Channel target detection data for the man-made targets. The tests compared the percentage of targets detected by each system for each run. Results show that the AN/APS-94D system was significantly better than the COR system for detecting man-made targets ($t = 2.91$; $t > 2.82$ at 9 degrees of freedom required for significance at the 0.02 level).*

Surface Slicks. A comparative analysis was made of the oil detection capabilities of AN/APS-94D and COR based on an evaluation of imagery from ten coincident radar runs flown over the western Santa Barbara Channel on May 19. Crude oil from natural oil and gas seeps in the Santa Barbara Channel and oleyl alcohol spilled at two locations provided reliable targets for evaluating the oil detection capabilities of both systems. Four distinct natural slicks, ranging in size from 3.9 to 6.0 square miles, were visible offshore between the coastal community of Summerland and the Capitan oil field (Figure 2). In addition, simulated oil slicks were created by the controlled release of small quantities of oleyl alcohol from the USCG cutter *Pt. Judith* by Naval Research Laboratory personnel. A small slick was established southwest of Platform Holly by releasing 300 grams of oleyl alcohol at two locations approximately 50 feet apart. The maximum extent of the merged slick was estimated at 80 by 120 feet. A much longer artifical slick was created by dispensing oleyl alcohol into the wake of the *Pt. Judith*. A total of 8.1 liters of the fluid was sprayed over the stern of the cutter, producing a strip approximately 2.25 miles long by 300 feet wide. Figure 2 shows the surface locations of natural and artificial slicks in the test area.

Wind direction during the May 19 test was 220° at 10 knots; swell direction was 270° with 3-foot waves (Figure 3). Sea state and wind speed were considered favorable for the radar tests. Under such conditions the sea surface provides good backscattering compared to oil covered areas, where a dampening or flattening effect on capillary waves reduces surface returns. During the tests, the OV-1D (AN/APS-94D) and C-47 (COR) radar aircraft flew a controlled box pattern above the test area. All OV-1D runs were flown at 6500 feet; the C-47 operated at 5500 feet. In order to minimize potential interference, the AN/APS-94D was tuned to 9100 MH_z while the COR was set on 9315 MH_z.

COR

During the ten imaging runs completed on May 19, COR consistently detected surface slicks associated with natural seepage. In addition, the long linear oleyl alcohol slick created during Run 6 was detected on subsequent runs. Detection of natural and simulated slicks was accomplished regardless of look direction. Only the small oleyl alcohol spill located southwest of Platform Holly was not detected. Failure to image the small spill was attributed to the limited surface areal expression of the slick which was smaller than the minimum resolution cell size of COR. Runs 0-8 were operated using a standard 0-25 km range setting. Run 9 was flown with a 20 km delay. The maximum range that oil was detected by COR at the 0-25 km range setting was 18.4 km. With a 20 km delay (20−45 km range setting) the maximum slant range distance at which oil was imaged was 26.1 km. These detection range figures should be used with care. Reasons for non-detection could include the decreased angles of incidence at these ranges or the lack of surface slicks beyond this range. With the exception of Run 4 (flown east-to-west and parallel-to-swell direction), the vertically polarized synthetic-aperture system provided excellent contrast between surface slicks and the ocean surface. Further, no significant loss of image integrity was experienced over coastal waters when the system was switched from over-

* The statistical test used in this evaluation paired the mean surface target detection results between the AN/APS-94D and COR systems for each run and computed a "*t*" statistic for the difference between the paired observations. The pairing of results between the two systems assumed that the only dependent variable is relative target detection capability and that all other variables were independent. Therefore, for the purposes of this test it was assumed that look direction, target location, and range to the target for the runs which were paired were either equal or sufficiently similar with respect to the two systems that their effect on the image quality was negligible. The following formula was used when conducting the paired statistical analysis:

$$t = \bar{d}/\left(\sigma/\sqrt{N}\right)$$

where $\bar{d}$ is the difference between the mean target detection for all AN/APS-94D runs and the mean target detectability of AN/APS-94D and COR systems, and N is the number of paired observations target detectibility of AN/APS-94D and COR systems, and N is the number of paired observations (i.e., runs).

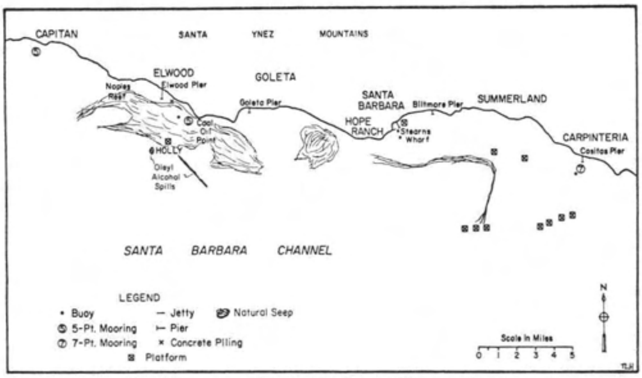

FIG. 2. Western Santa Barbara Channel test area.

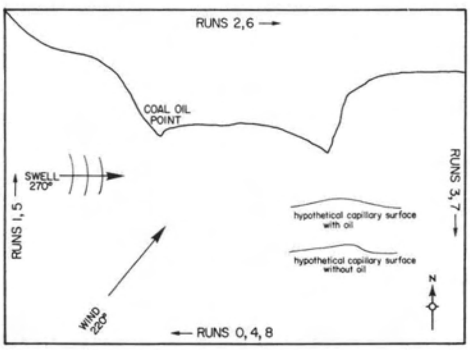

FIG. 3. Sketch map depicting approximate wind and swell directions in the western Santa Barbara Channel, May 19, 1976. Look direction from AN/APS-94D and COR perpendicular and to the right of the aircraft flight direction for each run.

land to overwater modes. Overall success rate for detecting natural and artificial surface slicks was 65.8 percent (25 of 38). However, if the small oleyl alcohol slick is excluded from consideration, COR's detection rate for surface pollution slicks increased to 83.3 percent of possible targets (25 of 30). Figure 4 illustrates the oil detection capability of COR using imagery from Runs 6 and 7.

AN/APS-94D

The horizontally polarized AN/APS-94D was less successful than COR in the detection of natural and artificial surface slicks. While COR detected more than 65 percent of the known slicks in the western Channel area, the real-aperture system operating in the overland mode imaged only 28.9 percent (11

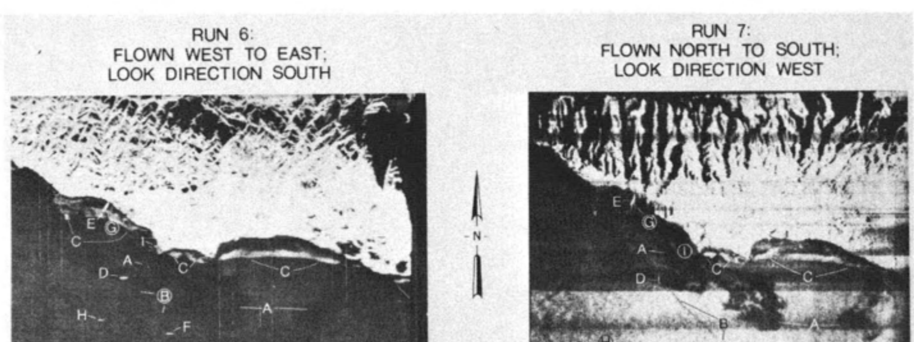

FIG. 4. Synthetic-aperture coherent-on-receive (COR) radar imagery of western Santa Barbara Channel test area flown May 19, 1976. Representative targets include: (A) natural seep oil slick; (B) oleyl alcohol slick; (C) kelp: (D) Platform Holly; (E) oil support pier—1900 feet; (F) USCG cutter *Pt. Judith*—83 feet; (G) aluminum crewboat—61 feet and wooden tug—83 feet; (H) fiberglass sailboat—40 feet; and (I) 5-point mooring and radar reflector buoy. A circle with a letter annotation indicates that a target was not detected.

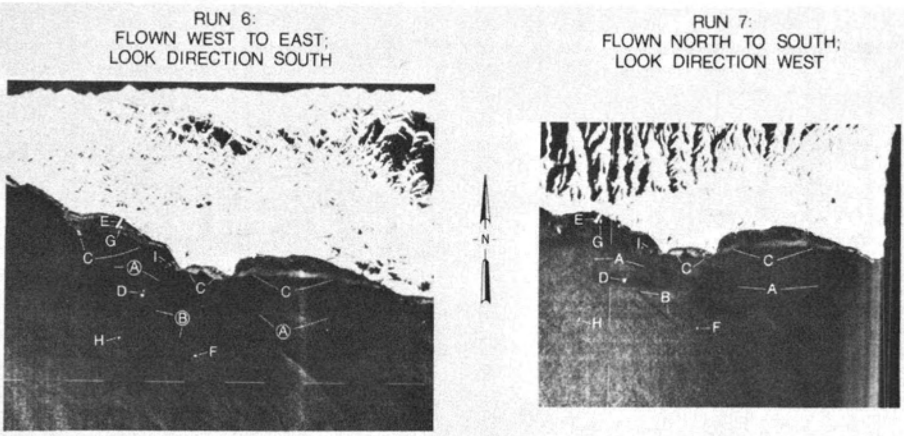

Fig. 5. Real-aperture AN/APS-94D radar imagery of western Santa Barbara Channel test area flown May 19, 1976. Representative targets include: (A) natural seep oil slick; (B) oleyl alcohol slick; (C) kelp; (D) Platform Holly; (E) oil support pier—1900 feet; (F) USCG cutter *Pt. Judith*—83 feet; (G) aluminum crewboat—61 feet and wooden tug—83 feet; (H) fiberglass sailboat—40 feet; and (I) 5-point mooring and radar reflector buoy. A circle with a letter annotation indicates that a target was not detected.

of 38). Again, the small oleyl alcohol slick was not detected. Elimination of the small slick as a possible target yielded a slight improvement in the AN/APS-94D percent detection rate, from 28.9 percent (11 of 38) to 36.7 percent (11 of 30).

In contrast to COR, the AN/APS-94D appears to be extremely dependent on look direction for oil detection. During the May 19 test, only Runs 3 and 7 provided good contrast between oil and water. The look direction on both these north-to-south runs was into the swell and somewhat across the direction of the surface wind (Figure 3). The eight remaining runs were flown with the look direction either perpendicular to, or with the swell direction. No oil was detected on Runs 0, 1, 4, 5, 6, and 9; only limited success was achieved on Runs 2 and 8. Figure 5 contrasts AN/APS-94D images for Runs 6 and 7. Runs 0-8 were flown using a 0-25 km range; Run 9 was flown at 0-50 km without a delay. Maximum oil detection slant range was 35.1 km operating at 0-50 km and 23.8 km using 0-25 km mode.

In order to determine if there was a statistically significant difference in the ability of the AN/APS-94D and COR systems to detect surface oil slick targets, a paired t-test was applied to the results of the May 19 Santa Barbara Channel data set. In contrast to the man-made target detection results reported earlier, the COR system detected the surface oil slicks significantly better than the AN/APS-94D system ($t = 3.69$; $t > 3.25$ at 9 degrees of freedom required for significance at the 0.01 significance level).

From the limited sampling data available, it is difficult to determine whether the poor performance of the AN/APS-94D against surface slick targets was attributable to the horizontally polarized antenna, incorrect gain settings, or a combination of these factors. Previous studies (Guinard and Purves, 1970; Krishen, 1972; Long, 1975) have documented that oil films reduce sea echo more for vertical than for horizontal polarization. Further over-water flight tests of real-aperture radars, using antennas of different sizes and polarizations, will be conducted by the Coast Guard in the near future in order to determine optimum polarizations and gain settings for oil slick detection.

Target Interpretability†

In addition to assessing target detectability, an additional evaluation of target interpretability was performed. This involved analyzing returns from known targets on each AN/APS-94D and COR run, then ranking these returns on an ordinal scale. Table 2 presents a summary of the target interpretability evaluations arranged by date, system, and type of target.

Overall, AN/APS-94D achieved a target

† Evaluation of target interpretability concentrated on image analysts' assessments of the sharpness and background contrast of AN/APS-94D and COR radar returns from man-made and surface slick targets. Technical data on theoretical ground range and azimuth resolutions for the systems employed in this test are contained in a Motorola, Inc. report to the Coast Guard (Fraser and Morris, 1976).

TABLE 2. TARGET INTERPRETABILITY

General Target Type	AN/APS-94D 5/19/76	COR 5/19/76	AN/APS-94D 5/20/76	COR 5/21/76
1. Man-made				
Possible targets	163	162	96	178
No. ranked good	139	82	75	119
No. ranked fair	15	14	18	33
No. ranked poor	2	25	..	17
% detected targets[A] ranked good	89.1	67.8	80.6	70.4
2. Surface Slick				
Possible targets	38	38	..	2
No. ranked good	8	20	..	..
No. ranked fair	1	4	..	..
No. ranked poor	2	1	..	..
% detected targets[A] ranked good	72.2	80.0		
3. All targets				
Possible targets	167	146	93	169
No. ranked good	147	102	75	119
No. ranked fair	16	18	18	33
No. ranked poor	4	26	..	17
% detected targets ranked good	88.0	69.7	80.6	70.4

[A] Excludes targets not detected.
Target Interpretability Key:
- Good—Target sharp and well-defined. Where targets were clustered, individual targets or components of individual targets (e.g., floats within a tanker mooring) were clearly discernable.
- Fair—Target readily identifiable, but lacked sharpness and clarity. Individual targets often merged together or with image background.
- Poor—Target identifiable only through prior knowledge of exact location. Return lacked sharpness and characteristically merged with background; separate components of individual targets (e.g., floats in a tanker mooring) could not be discriminated.

interpretability rating of "good" for over 80 percent of the targets detected on both May 19 and 20. Conversely, COR was rated "good" for only 69.7 percent of the detected targets during the May 19 coincident overflights, and 70.4 percent against all targets on May 21. Returns from man-made targets were consistently interpreted as appearing sharper on AN/APS-94D imagery as compared to returns from the same targets imaged by COR. This clarity permitted more reliable discrimination of multiple targets by AN/APS-94D in cases where targets were located in close proximity to one another (e.g., individual floats in a 5-point tanker mooring). In addition, this sharpness facilitated the identification of targets in areas with high background reflectance (e.g., within or adjacent to kelp beds). Conversely, closely spaced man-made targets often merged on the COR imagery, making it difficult or impossible for an interpreter to discriminate individual targets. This reduction in interpretability may have been a function of gain, mode setting, or the multiple-look features of COR. A *t*-test was applied to the paired AN/APS-94D and COR May 19 data set to determine if there was a significant overall difference in the interpretability of man-made and surface slick targets imaged by the two systems. This analysis concluded that interpreters rated AN/APS-94D images as being significantly more interpretable than those produced by the COR system ($t = 3.17$; $t > 2.82$ at 9 degree of freedom required for significance at the 0.02 level).

CONCLUSIONS

Major findings which can be drawn from an analysis of the data acquired during this test flight program are summarized:

- *Detection of man-made targets.* The AN/APS-94D system detected man-made targets (fixed or moving) from a variety of look directions and ranges significantly better than the COR system.
- *Detection of surface oil slicks.* The COR system detected surface concentrations of oil from all directions significantly better than the AN/APS-94D system. The AN/APS-94D detected oil only when the system was looking approximately into the direction of wind and swell.
- *Overall target interpretability.* Target returns on AN/APS-94D imagery were judged by interpreters to be significantly sharper and more interpretable than those on COR.

This permitted reliable discrimination of multiple targets located in close proximity to one another or targets in areas with high background reflectance. Conversely, COR often merged closely spaced targets and failed to discriminate individual targets from other background returns.

Although data derived from the flight test program answer many questions concerning the offshore target detection and interpretability characteristics of AN/APS-94D and COR imagery, a number of basic questions remain, including:

- The reasons for non-detection of oil by AN/APS-94D except when looking into the swell direction, and
- Determination of optimum and maximum detection ranges of both systems for man-made and natural surface targets under a variety of sea states and operating conditions.

Acknowledgments

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