Radar Performance During Propagation Fades in the Mid-Atlantic Region

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Abstract— **Periodically through the year, an Atlantic coast vessel traffic control radar, located near the entrance to the Delaware Bay, observes a reduction in detection range from 37 (20 nmi) to about 17 km (9 nmi). Sometimes ships can be seen visually from the radar tower before they can be observed on the radar screen. The reduction in the radar detection range usually lasts several hours and occurs often when fog is present. An investigation of this phenomenon, referred to as a radar deep fade (RDF), was undertaken to find out what causes the fade and to determine the best method of increasing the radar detection range when one occurs. The investigation indicated that these RDF's arose during the presence of a propagation condition known as subrefraction, which is an increase in the atmospheric index of refraction with altitude above the ocean surface at microwave frequencies. This increase in the index of refraction with altitude results in the effective radius of the earth being much smaller than the usual 4/3 earth radius that is observed for radars during standard atmospheric conditions. During subrefractive conditions, the effective earth's radius can be between its true radius and one-half of its true radius. As a result, the radar horizon is shortened and the radar detection range is reduced. These RDF's will occur during propagation conditions known as sustained deep fades (SDF's), which arise when subrefraction lasts for more than two hours and causes one-way losses exceeding 20 dB relative to free-space for line-of-sight (LOS) geometries. Subrefraction is caused by the movement of subtropical moist air over the cold ocean surface. The recommended solution for increasing the radar range in the presence of subrefractive conditions is to place the radar on a higher tower than the present 19-m-high tower, one that is perhaps 60-m high. This would increase the radar range by 50% when the earth's effective radius is half of normal. This increase in radar height also usually increases radar detection performance when skip zones associated with surface-based ducts occur or when evaporation ducts (EVD's) are present.**

I. Introduction

RADAR detection range in the Delaware Bay area is periodically reduced to a fraction of normal and is usually correlated with fog. This problem has been encountered by many radar operators in this area and was brought to the authors' attention by the Pilots Association for the Bay & River Delaware.

The Pilots Association provides piloting services for all ports from the Delaware Bay to Trenton, NJ. They maintain a pilot house, jetty, several launches, radio tower, and a radar site at Cape Lewes, Delaware, for the detection and tracking of ship traffic. Radar site equipment is composed of two 3.6 m S-band antennas, two 60-kW transceivers, and a radar display and tracker. The antennas are horizontally polarized slotted arrays with 1.85° azimuth and 22° elevation beamwidths and are located at a height of 19 m above mean sea level (AMSL).

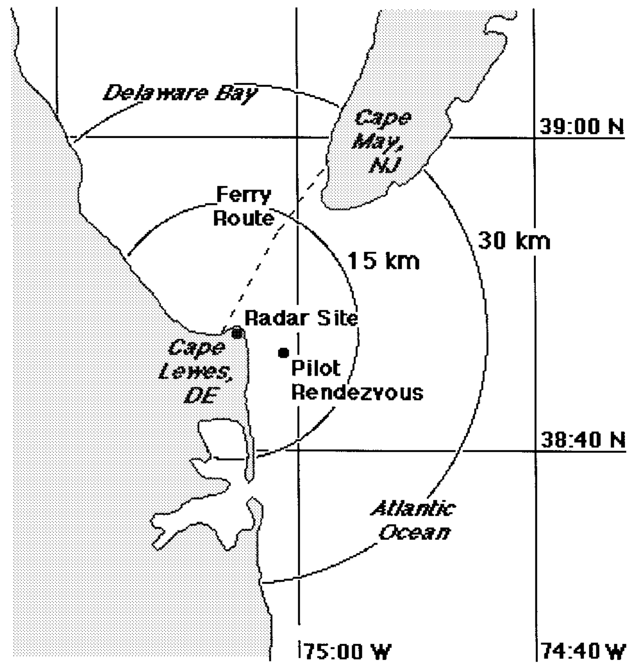

Fig. 1. Map of the mouth of the Delaware Bay illustrating the location of the radar site at Cape Lewes, the extent of radar coverage, and the ferry route.

In order to provide timely services, the Pilots Association uses the radar to detect large commercial shipping vessels as they approach the Delaware Bay. The vessel types vary from barges under tow by tugs to container and cargo ships and oil tankers. When a ship is contacted and piloting services required, arrangements are made to board a pilot at the rendezvous point (see Fig. 1). Similarly, as a ship leaves port, it is guided out to the rendezvous point by a pilot, who is then transferred to a waiting launch for return to the pilot house at Cape Lewes.

Captains M. Linton, P. Ives, and W. Lowe of the Pilots Association provided much of the information about the radar performance and described the problem as follows. Radar detection range for ships of interest decreases from a typical range of 37 km (20 nmi) from the radar site to approximately 19 km (10 nmi). At times, ships can be seen visually from the radar-tower control room long before the radar acquires them. The decrease in detection range lasts for several hours before returning to normal. It is usually associated with fog and occurs both over the ocean and over the bay. This phenomenon will be referred to as a radar deep fade (RDF).

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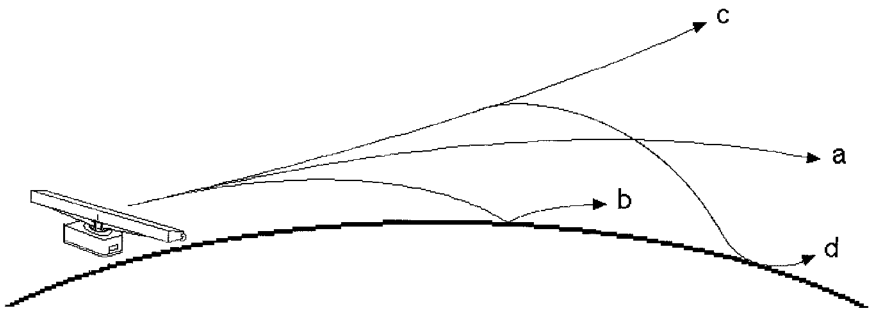


Fig. 2. The effect of refractive conditions on radar waves for: (a) standard atmosphere; (b) evaporation duct (EVD); (c) sustained deep fade (SDF); and (d) skip zone.

The Pilots Association reports that RDF's occur often throughout the year and that one particular RDF incident was recorded in the Pilots Association Breakwater Weather Report on August 5, 1994. An excerpt from the record is shown in Table I. Note that the reduction in radar range lasts for a period in excess of four hours.

Corroborating evidence of this fade was provided by Mr. Charles Parker, who has been working with vessel traffic control radars for 20 years. On the same morning of August 5, 1994, Mr. Parker was taking the ferry from Cape May and was invited by the ships captain to view the radar displays. Since visibility at the time was severely limited by fog, navigational information was provided by the radars. Radar range was limited to several nautical miles and Cape May showed up on the plan position indicator (PPI) display as only a few land clutter speckles. Typically, the Cape is brightly displayed along many miles of its coastline and radar range exceeds 28 km (15 nmi). As shown in Fig. 1, the Cape May-Cape Lewes ferry provides scheduled service between the two points along an established route. This ferry has both X-band and S-band marine radars for use in navigation and collision avoidance, with antenna heights of approximately 18 m AMSL. The noted reduction in detection range was observed on both the X- and S-band systems.

Another related phenomenon has also been reported by the Pilots Association. As a ship enters the radar coverage area at approximately 37 km (20 nmi), it is detected and tracked for several kilometers. As the ship continues its course toward the Delaware Bay, it fades from the radar display at about 22 km (12 nmi) and is not seen again until it is within 11–15 km (6–8 nmi) of the radar site. Again, the ship can usually be seen visually from the radar tower control room long before the radar can re-acquire it. This phenomenon is referred to as a skip zone and reports show that it occurs over the ocean but not over the bay area.

Radar detection performance during RDF's and skips zones has been investigated to determine the possible causes. Detection at long ranges ($>$37 km) allows the Pilots Association to meet ships at rendezvous without any delay for the ships. The operating cost of a cargo ship may range from $10 000 a day for general tramp cargo to $25 000 a day for liquid propane gas (LPG) tankers, so any delay at rendezvous due to loss in radar coverage is costly to the Pilots Associations clients [1].

II. Background

Extensive reductions in radar coverage, like the events that occurred in the Delaware Bay area, are the result of anomalous atmospheric conditions affecting the path of the radar signal. In standard atmospheric conditions the pressure, temperature and water vapor content of the air decrease with increasing height above the surface. This causes the refractivity (N) to decrease at a rate between 0 and -79/km where N is defined as

$$N = (n-1)10^6$$
$$n = \frac{c}{v}$$

and n is the index of refraction, c is the velocity of the radio wave in free-space, and v is its velocity in the medium. This decrease in N with height affects radar waves by bending them slightly toward the surface of the earth (path a in Fig. 2). As a result the radar sees further beyond the horizon than if N did not decrease with height. This has the effect of flattening the earth or increasing its effective radius. In fact, there is an equivalent earth's radius factor (k) that allows the rays to be drawn as straight lines. For a constant gradient of N with altitude of -39 N/km [shown in Fig. 3(a)], we obtain the well-known 4/3 earth equivalent radius factor (i.e. $k = 4/3$) [2].

Meteorological conditions often create a refractivity gradient with height that deviates significantly from a standard profile and causes anomalous propagation. When the resulting atmosphere has a decrease in N that is greater than a standard atmosphere, superefraction occurs and the electromagnetic waves are bent downward more than in the standard case. If this rate of decrease exceeds -157/km, a condition known as trapping is created where radio waves propagate in an atmospheric duct. One particular type of duct, known as an evaporation duct (EVD) (path b in Fig. 2), is caused by the rapid decrease in water-vapor pressure with increasing height above the ocean surface [3], [4]. These ducts extend radar coverage significantly and have the effect of flattening the earth even more than the standard refractivity profile. EVD's are frequently present over the ocean surface and the Delaware Bay area has an average duct height of 14 m [5]. An example refractivity profile of a 14-m EVD is illustrated in Fig. 3(b).

Atmospheric conditions that create an increase in N with height $(dN/dh > 0$ N/km) are subrefractive and force radar signals to refract upward away from the surface (path c in

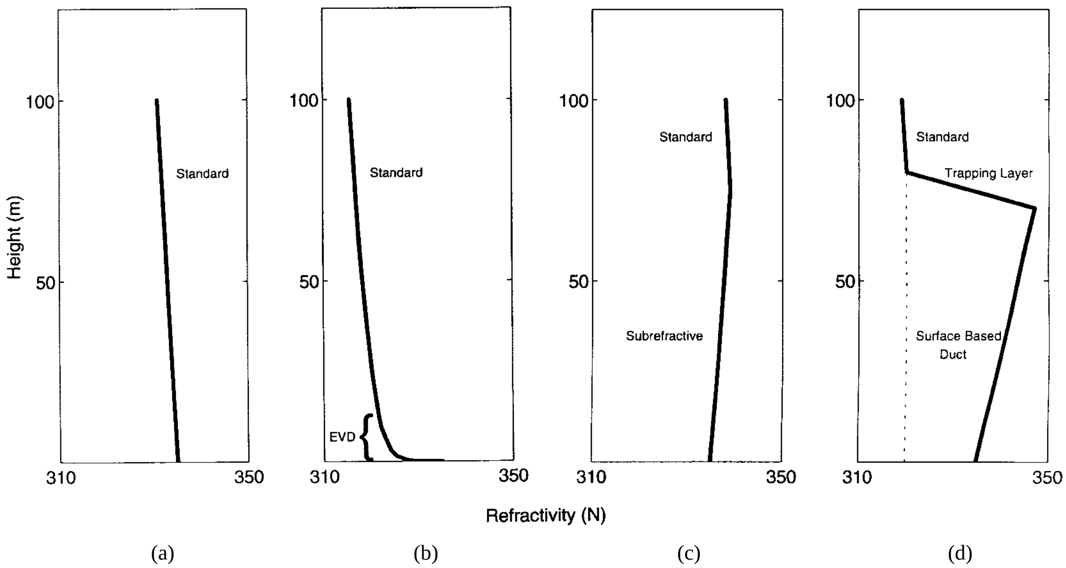


Fig. 3. Refractivity profiles of: (a) standard atmosphere (−39 N/km); (b) evaporation duct [14-m EVD profile from engineers refractive effects prediction system (EREPS)]; (c) SDF (54 N/km from Wallops Island radiosonde data); and (d) skip zone (170 N/km up to 70 m and elevated trapping layer from 70 to 80 m).

Fig. 2). This has the effect of decreasing the equivalent earth radius factor to as little as $k = 1/2$ (compared to $k = 4/3$ for a standard atmosphere) causing the radar horizon to be reduced significantly. In extreme subrefractive atmospheric conditions, radar detection is limited by large losses in signal power known as propagation fades and, as a result, radar coverage is severely degraded. When the propagation fade from subrefraction lasts for more than two hours and causes one-way losses exceeding 20 dB relative to free-space, a condition known as a sustained deep fade (SDF) occurs [6], [7]. A sample refractivity profile obtained during an SDF is shown in Fig. 3(c). For this SDF, the rate of increase of N with altitude is 54 N/km, which corresponds to an effective earth radius of 0.744 times the actual earth radius. The refractive conditions that cause an SDF are precisely the conditions that are observed during an RDF and the two appear to occur together. SDF's do not occur, however, when EVD's are present and vice versa.

Goldhirsh *et al.* [7] studied the meteorological causes of SDF's using a one-way C-band propagation link and refractivity profiles obtained from meteorological equipment on a helicopter and on radiosonde balloons. The measurements, which were taken over water in the mid-Atlantic region during a three-year period, show that signal attenuations greater than 20 dB and as high as 60 dB correspond with the occurrence of extreme subrefractive atmospheric conditions. In addition, these measurements show that SDF's usually occur when subtropical moist air travels northward along the mid-Atlantic coast at the same time as a cold front in the southern states moves eastward and traps moisture along the coast. The resulting warm moist air over the colder water creates a surface based temperature inversion and causes the saturated vapor pressure to increase with height. These meteorological conditions are also conducive for the development of fog [6].

The occurrence of the RDF recorded by the Delaware Pilots Association on August 5, 1994 coincided with a shift in wind direction and a reduction in visibility with the onset of fog. Radiosonde data is not available for the Delaware Bay area, but the recorded weather data for that day (see Section III for details) indicate that a front of moist air was moving into the region from west to east. It is likely that these conditions caused an increase in saturated vapor pressure with height and created a subrefractive layer in the atmosphere, which is exactly the refractive conditions needed for an SDF.

When propagation fades at short range are followed by signal enhancement at long range, they are referred to as skip zones (path d in Fig. 2). These are caused by surface-based ducts that form when warm dry air passes over cooler air close to the ocean surface causing a trapping layer that is elevated above the surface [5]. The refractivity profile of a surface-based duct that might cause a skip zone in radar coverage is illustrated in Fig. 3(d). These surface-based ducts are present about 8% of the time, are usually associated with fair weather, and are more common in warmer weather and more southerly latitudes [8]. The range and extent of the skip zone effect is a function of the duct height, radar antenna height, and the slope of the refractivity profile.

III. Analysis

Evidence of SDF atmospheric conditions coinciding with the occurrence of the RDF on August 5, 1994 is provided by the aforementioned Johns Hopkins University Applied Physics Laboratories (APL), Baltimore, MD, test-bed pair of C-band, over-water, line-of-sight (LOS) propagation links in the mid-Atlantic region. These C-band links are located approximately 120 km from the Cape Lewes Radar site (as illustrated in Fig. 4) and share the same macro weather patterns [9]. Fig. 5(a) and (b) shows the propagation fade measured on August 5, 1994 by the C-band link between Paramore Island and the Lookout Tower and between Paramore Island and the Lighthouse, respectively. These data show an SDF starting in the early morning and continuing until about 1600 EST in the afternoon. The fade exceeded 30 dB for the lighthouse link and

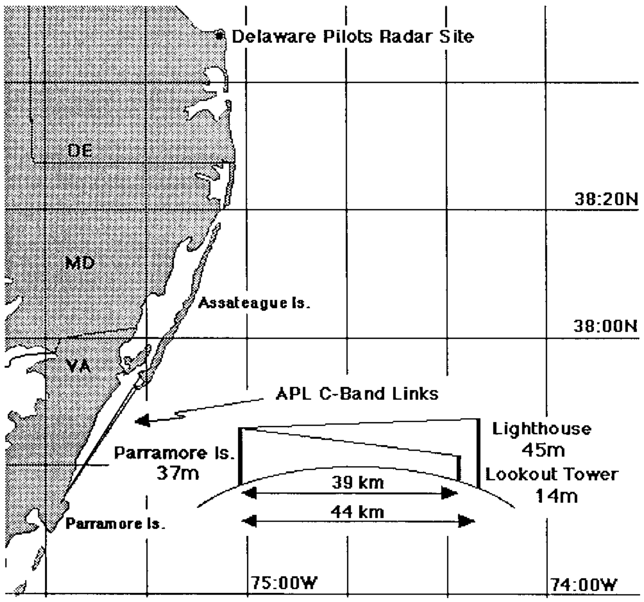
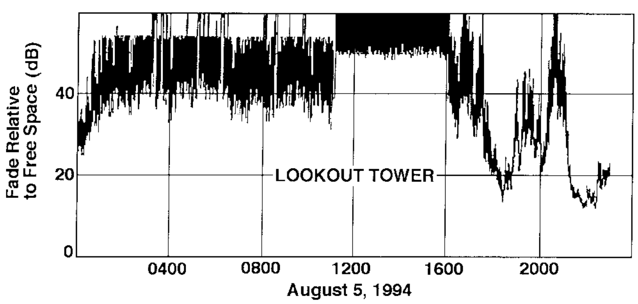
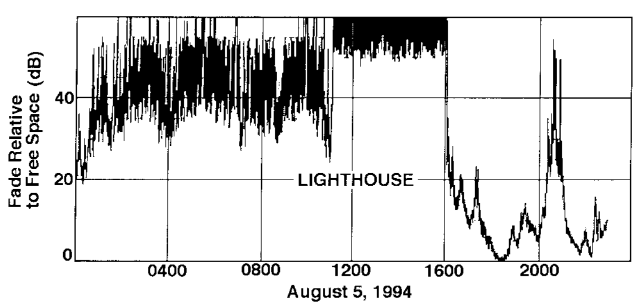


Fig. 4. Location and geometry of the APL C-band links in relation to the location of the Delaware Pilots radar site at Cape Lewes.



(a)



(b)

Fig. 5. APL C-band link propagation fade data taken on August 5, 1994 between (a) Paramore Island and the Lookout Tower and (b) Paramore Island and the Lighthouse.

35 dB for the lookout tower link, with an even more severe fade from 1100 to 1600 when the weather front moved directly over the area. This corresponds closely with the Delaware pilots weather record data provided in Table I.

Weather maps provided by the National Climatic Data Center (Asheville, NC) for several times on August 5, 1994 indicate that classical conditions existed for the presence and ending of a deep fade along the Atlantic coast [6], [10]. Specifically, Fig. 6 shows the weather map for 1100 EST on August 5, 1994, a time during which the RDF was present according to the Delaware pilot's weather record. This weather map shows a high-pressure system to the East of the Cape Lewes radar site. This high-pressure region causes a clockwise flow of the air around the high-pressure site (see Fig. 6). As a result, the subtropical moist air moves northward over the Mid-Atlantic coast and over the subtropical Atlantic. At the same time, there is a low-pressure system to the north along the coast. The air flows counterclockwise around the center of this low-pressure region further resulting in the movement of subtropical moist air northward along the Mid-Atlantic coast from the Gulf of Mexico. Another characteristic seen when an RDF is present is an eastward traveling cold front that resides west of the coast. This cold front traps the moist air along the Atlantic coast. The passage of the moist air over the cold water results in a surface-based temperature inversion, i.e., the temperature increases with increasing altitude near the surface instead of decreasing. This, in turn, causes an increase of the saturation vapor pressure with altitude with the result that the atmosphere holds increased moisture with increased altitude. Since the index of refraction at microwave frequencies is proportional to the partial pressure of the water vapor, the temperature inversion causes the index of refraction to increase with altitude. The result is a refractivity profile similar to Fig. 3(c), or that of an SDF. When the eastward moving cold front passes over the radar site, cooler, less humid air passes over the coastal region resulting in the termination of the conditions for a deep fade. The weather maps indicate that the cold front passes over the radar site at approximately 1700 EST, which is consistent with the Pilots Association log shown in Table I. Thus, the weather maps for August 5, 1994 further suggest that the conditions for creating SDF atmospheric conditions are causing the RDF's. The above noted increase in index of refraction with altitude does not occur at visible wavelengths because at those frequencies the index of refraction is not dependent on the partial pressure of the water vapor [16]. As a result, the visible rays do not bend upward as they do for microwave signals. It is for this reason that the ships are visually visible, but are not observed on the radar display when the RDF is occurring.

TABLE I
PILOTS ASSOCIATION WEATHER RECORD FOR AUGUST 5, 1994 (∗ REPRESENTS MISSING DATA IN RECORD)

Time (EST)	Wind (Dir/kts)	Sea Condition	Sky	Visibility (nmi)	Radar Range (nmi)
0400	S/12	Small	Clear	15	20
0800	SSW/15	Small	Clear	5	9
1200	SW/12	Small	Showers	6	11
1600	NW/25	Choppy	Showers	0.5	*
2000	NNE/20	Moderate	Overcast	10	20
2359	N/20	Moderate	Overcast	15	20

Detection performance for the Delaware Pilots Association radars was evaluated using the standard radar-range equation. Radar parameters were obtained from published data sheets for the marine radars used at the Cape Lewes site. The signal-to-noise ratios (SNR's) presented in this analysis were calculated

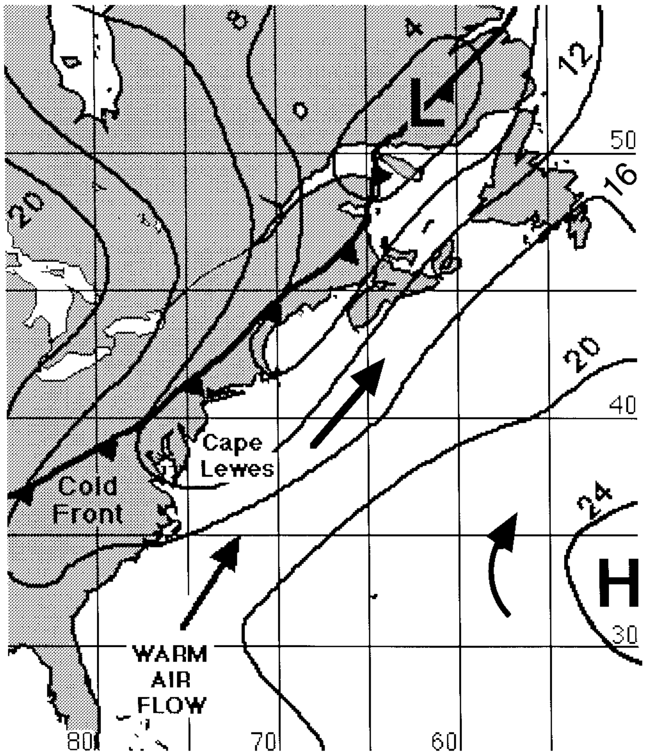


Fig. 6. Coastal United States weather map for 1100 EST on August 5, 1994.

using

$$\mathrm{SNR} = \frac{P_t \tau G^2 \sigma \lambda^2 F^4}{(4\pi)^3 R^4 k T_s L}$$

$$P_t = 60 \text{ kW}$$
$$t = 1 \text{ msec}$$
$$G = 28 \text{ dB}$$
$$l = 0.983 \text{ m}$$
$$T_s = 2000°\text{K}$$
$$L = 12 \text{ dB}$$

where the estimated loss term (L) includes transmission line loss, filter-matching loss, constant false alarm rate (CFAR) loss, scan loss, and binary integration loss and is Boltzman's constant. The two-way propagation factor (F^4), which was modeled using the electromagnetic parabolic equation (EMPE) propagation program [11], is equivalent to twice the negative value of propagation fade.

The refractivity profile used for the deep-fade analysis is from a similar subrefractive event [Fig. 3(c)] recorded on March 16, 1990 using balloon launched radiosonde data from Wallops Island, VA (approximately 110 km from Cape Lewes) [9], [12]. The refractivity profiles for short range skip zones, as encountered by the Delaware pilots, are based upon surface-based ducts [Fig. 3(d)]. These conditions typically occur over the ocean and on the leeward side of land masses, which agrees with the Pilots' reports that skip zones occur only over the open ocean and not in the Bay area. Surface-based ducts have been recorded in the mid-Atlantic region and the average measured height of the elevated trapping layer is between 62 and 127 m [5]. For this analysis of skip zones, a surface-based duct with an elevated trapping layer height of 80 m was used.

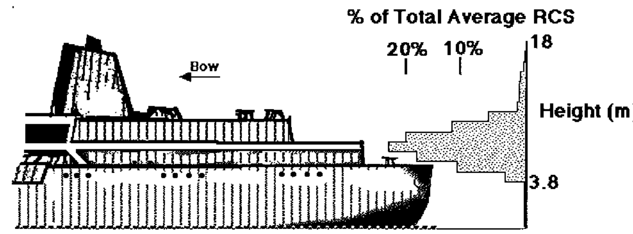


Fig. 7. Distributed RCS model for the tanker Chilbar, which entered the Delaware Bay during the August 5, 1994 recorded RDF event.

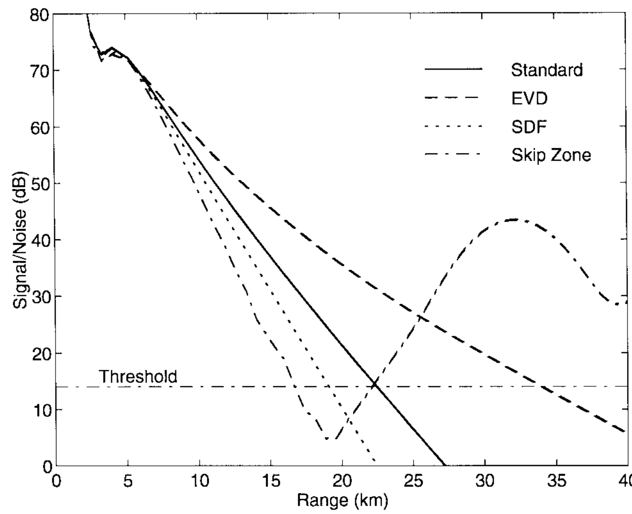


Fig. 8. Performance of the Cape Lewes S-band radar during each of the atmospheric refractivity conditions illustrated in Fig. 3.

The radar target used for the analysis is modeled on a commercial tanker, the United States flagged Chilbar, which was recorded in the Delaware Pilots shipping log as inbound from New York City during the August 5, 1994 RDF event. For such a large target there will be considerable variation in microwave reflection with height due to the various properties of the hull, superstructure, masts, etc. of the ship. The distributed radar cross section (RCS) target model [13] shown in Fig. 7 was, therefore, used to provide a more accurate measure of the total target radar return. The RCS (σ) of the tanker is estimated at 35 dB based on measurements of similar ships [14]. A scan-to-scan Rayleigh target fluctuating model (Swerling Case 1) was assumed for this analysis.

Using these radar, target and propagation models, the radar SNR shown in Fig. 8 was calculated for the profiles given in Fig. 3, a standard refractivity profile, a 14-m EVD profile, an SDF subrefractive profile, and a skip zone surface-based duct profile. The detection threshold of 14 dB is based on a probability of detection of 0.9, a probability of false alarm of 10^{-6}, and approximately ten pulses hitting the target per scan [15].

Very good agreement is found between predicted and actual performance as described by the Delaware Pilots. During SDF atmospheric conditions the radar range is reduced by as much as 50% from nominal performance and during surface-based

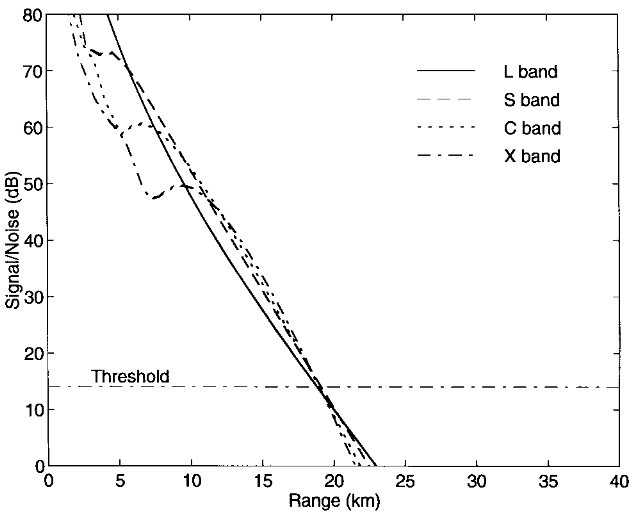


Fig. 9. Radar performance during SDF refractivity conditions for various microwave frequency bands.

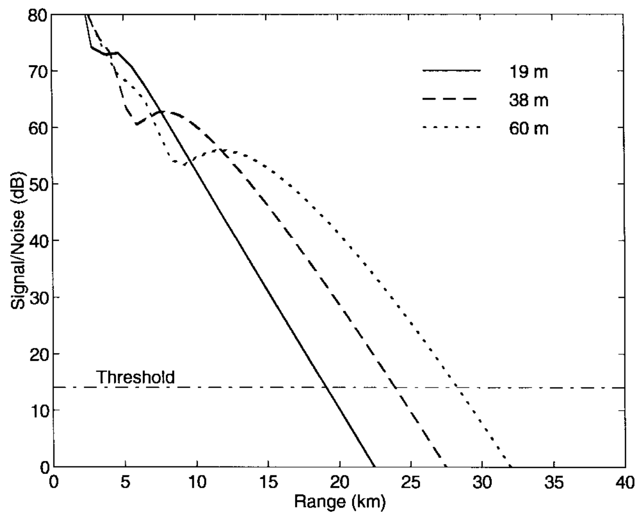


Fig. 10. Radar performance during SDF refractivity conditions for three antenna heights.

duct conditions significant skip zones or gaps in radar coverage exist. While RDF's have been correlated with fog, the attenuation due to fog is too small to account for the degradation in performance (about 0.02 dB/km two-way attenuation at S-band and 0.2 dB/km at X-band in heavy fog [16]). Having established a performance baseline that closely agrees with propagation fade ground truth data, various modifications to the radar configuration may be examined to determine the best method of improving performance under these adverse propagation conditions.

Increasing the SNR of the radar system is the first and most obvious method of overcoming the RDF's that occur during SDF refractivity conditions. To increase the radar detection range by 50% (equivalent to extending the detection range for the SDF condition in Fig. 8 to 29 km), the signal power must be increased by 40 dB. Since the radar systems at Cape Lewes already have 60-kW transmitters, this means increasing the transmitter power to 600 000 kW. Using such a high-power transmitter is out of the question. Similarly, increasing the antenna gain to obtain the additional 40 dB requires a S-band antenna that is about 9 m in diameter. This approach involves considerable development work for the antenna, its motor and the radar sensitivity time constant (STC) circuit that copes with the strong close-range echoes. There is also the issue of wind loading on the large antenna. A new tower would have to be built because the present one could not support this large antenna. The use of a larger antenna was, therefore, not deemed an attractive solution.

Frequency diversity is another method that is often used to overcome adverse detection conditions. Marine radars typically operate at S band (3.050 GHz) and X band (9.375 GHz) where the attenuation and backscatter due to rain and fog is small. Fig. 9 shows the SNR in an SDF atmosphere for various microwave bands. These results indicate that improved range performance is not achieved by going to other frequencies in the microwave band. In order to obtain the 40 dB necessary to increase the detection range by 50%, a frequency in the HF band must be used. This requires an extremely large antenna and presents additional problems, such as decreased resolution.

An alternative method of improving the detection capabilities in SDF's is to increase the radar antenna height. Fig. 10 shows the resulting SNR for an antenna height of 19 m (height of the current radar systems at Cape Lewes), 38 m (standard antenna tower height of 125 ft) and 60 m (standard antenna tower height of 200 ft). As Fig. 11 illustrates, increasing the antenna height effectively increases the radar horizon. The radar system with a 60-m antenna height experiences almost 40 dB less propagation loss during deep fades than the 19-m system and the one at 38-m experiences 20 dB less. Therefore, the amount of RDF that occurs during an SDF refractive condition can be reduced by moving the antenna to a higher location or placing the antenna on a higher tower. This analysis agrees with the C-band link study, which showed that over the three-year period, the lighthouse (height of 45 m) experienced a significantly smaller amount of propagation fade than the lookout tower (height of 14 m) [17]. Due to the relatively flat area surrounding the Cape Lewes radar site, increasing the antenna height requires installing a new tower. Placing the antenna at a higher height of 38–60 m has the disadvantage of slightly reducing the very near-in coverage of the radar due to the beam looking beyond the near-in region when placed higher up. At present there are two S-band radars at the same height of 19 m, the second being used for redundancy. To eliminate this loss of near-in coverage, it is recommended that one of these antennas be kept at the present height while the other be moved up to a higher height. Doing this, as we shall see, also helps with coverage during skip zone conditions and EVD conditions.

Reducing skip zones in radar coverage due to surface-based ducts is extremely difficult because the height of the elevated trapping layer may vary significantly with range and over time. Fig. 12 shows the radar SNR in the surface-based duct refractivity conditions of Fig. 3(d) for the antenna heights of 19, 38, and 60 m. Increasing the antenna height to 60 m moves the location of the coverage gap out beyond 30

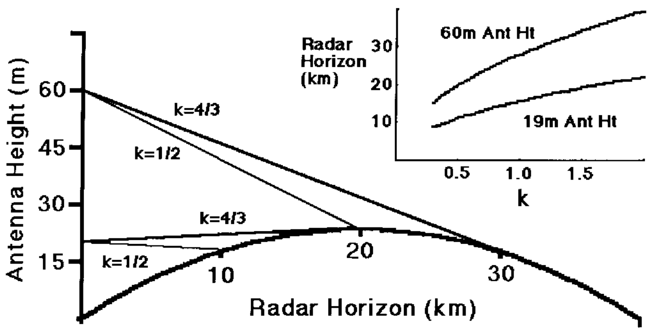


Fig. 11. Illustration of radar horizon for $k = 1/2$ and $k = 4/3$ and variation in radar horizon for all values of k (inset).

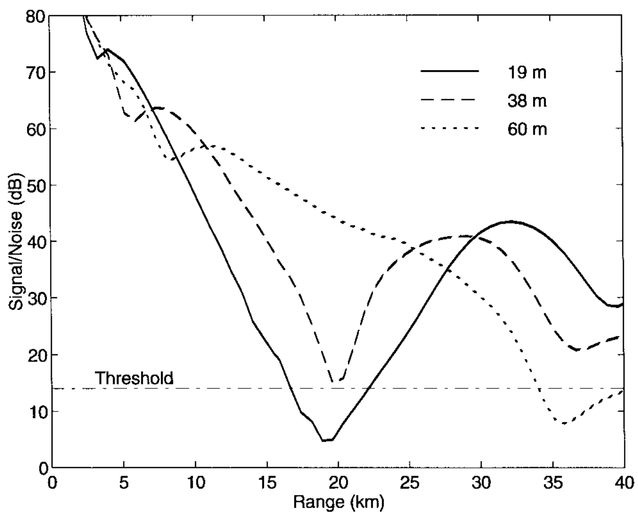


Fig. 12. Radar performance during surface-based duct refractivity conditions for three antenna heights.

km. Due to the elevated trapping layer, surface-based ducts also create increased detection capabilities at extended ranges (see Fig. 12). The range at which the coverage gaps occur and the extent of the overall coverage changes with the height of the elevated trapping layer in the surface-based duct. Measurements of surface-based duct profiles show variations as large as 50 m in the mid-Atlantic region. To cope with skip zone conditions it is apparent that it would be best to have antennas at two different heights as recommended for the RDF conditions.

It is important to point out that the skip zone selected in Fig. 3(d) is not the model generally used. For a typical surface-based duct, a standard atmospheric gradient is normally used below and above the trapping layer. Here we have used a subrefractive gradient below the trapping layer of 170 N/km which corresponds to a 0.480 earth radius, the subrefractive conditions observed by Goldhirsh *et al.* [7] on April 1, 1993. A typical surface-based duct was found to produce a dip in the SNR as a function of range, but the dip was not sufficient to produce a loss of detection for the target model, radar parameters and trapping layer height assumed for the Delaware Bay area. It was necessary to use a subrefractive gradient below the trapping layer to produce the skip zone shown in Figs. 8 and 12. With the subrefractive gradient

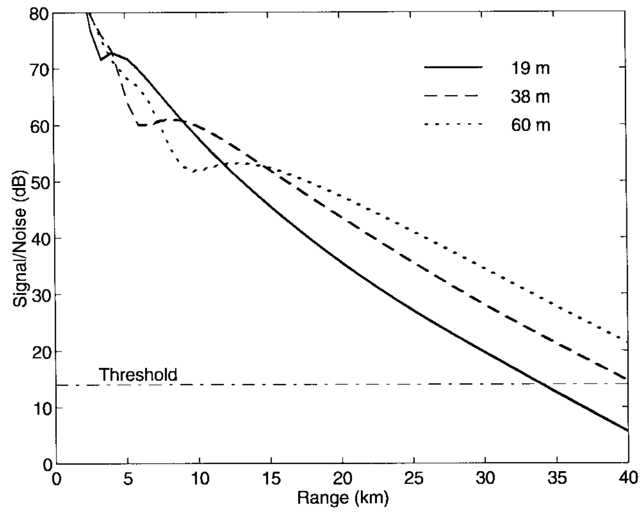


Fig. 13. Radar performance during EVD refractivity conditions for three antenna heights.

below the trapping layer, the rays rise fast enough to produce a loss of detection between 17 and 22 km for a 19-m radar height. What we have with our surface-based duct is actually a subrefractive-type condition, like in Figs. 3(c) and 8, but more severe with a trapping layer above it. For our surface-based duct it is the severe subrefractive conditions that cause the loss of detection at short range and the mirror-like trapping layer above it that produces enhanced detection at long ranges. The situation for subrefraction and our surface-based propagation are thus actually very similar. Both involve loss of effective range close-in due to diffraction, which results in a reduction in the effective earth radius. Fig. 8 shows that having standard atmospheric conditions below the trapping layer for the surface-based duct model does not produce a loss of detection; the detection range goes out to 22 km and is just beyond where the skip in detection occurs for the surface-based duct model used here. If a lower target cross section was used for this analysis, then a skip zone in detection would occur with a standard atmosphere below the trapping layer. A fruitful area for further future work is that of relating the occurrence of a skip zone to the meteorological conditions just as has been done by Goldhirsh *et al.* [7] for SDF's. It would also be desirable to obtain data on the frequency of occurrence of such radar skip zones. One of the reviewers of this paper expressed the opinion that the conditions of a subrefractive gradient capped by a trapping layer may occur more frequently than most radar propagation experts realize.

RDF's, due to SDF's and skip zones, severely limit radar detection capabilities, but it is important that the proposed method of reducing losses in these conditions does not degrade performance during normal atmospheric conditions. As Fig. 13 shows the detection range in EVD's, which occur frequently in the Delaware Bay area, is increased (35% for the 60-m antenna height and 20% for the 38-m antenna height) by increasing the antenna height. Therefore, having a dual-antenna radar system with two antenna elevations provides increased coverage in both nominal and anomalous propagation conditions. If cost prevents the dual-antenna configuration, then one antenna at a higher height would still improve overall performance.

IV. Conclusions and Recommendations

Reduction of the detection range by a factor of as much as two of the S-band marine radar near the entrance to the Delaware Bay has been noted when the conditions for severe subrefraction exist. This degradation in performance delays piloting services and is very costly to the shipping industry. It has been shown in this paper that the radar range could be increased by up to 50% during these severe subrefractive conditions by increasing the height of the antenna from 19–60 m. Increasing the antenna height was also shown to eliminate skip zones coverage conditions at the expense of a small decrease in the far-range coverage and to improve coverage during EVD conditions. As indicated the site at present has two S-band radars with both antennas at a height of 19 m, the second being used for redundancy. For best coverage results under all conditions, it is recommended that one of these antennas be left at the present altitude of 19 m, while the other be moved up to an altitude of 38–60 m on a new tower. When this is done it is recommended that the coverage provided by the these two radars is monitored to establish the advantage offered by having the radar at the higher versus lower altitude and by having radars at the two altitudes. If it is not deemed desirable to have the two radars operating simultaneously for cost or other reasons, then it is recommended that one radar be operated with an antenna at a higher height of 38–60 m. Although this analysis applies specifically to the Delaware pilots radar configuration, these results can be applied to all marine radars experiencing RDF's due to anomalous propagation conditions.

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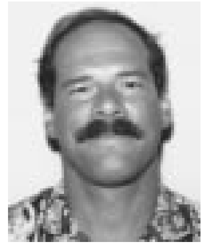

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