Lidar description of the evaporative duct in ocean environments

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ABSTRACT

The description of radar propagation in the presence of the evaporation duct has proven to be a difficult problem in both littoral and open ocean environments. To properly characterize the propagation of a radar beam at low elevation angles, the evaporation duct must be located and scattering properties quantified. The two key elements defining an evaporation duct are the gradients in density and specific humidity. The gradients of the neutral density are determined from the rotational Raman temperature profile. The profile of water vapor is measured directly from the vibrational Raman scattered returns. High spatial resolution and high temporal resolution measurements of water vapor and temperature are required to accurately describe the evaporation duct. Raman lidar techniques can provide these measurements continuously with high accuracy and high resolution so the development of the evaporation duct can be studied. A detailed simulation of a Raman lidar has been developed and applied to a near horizontal path, to examine the expected accuracy for high vertical resolution profiles. The simulation also allows various atmospheric scenarios to be investigated and analyzed. The evaporation duct is an atmospheric phenomenon that causes radar propagation to remain trapped in the surface layer. The duct can be thought of as a waveguide that bends and reflects the radar beam along a path effectively trapping it and guiding it over long distances. This is a major problem for radar propagation paths in both littoral and open ocean environments. Moreover, ducting skews details of radar returns such that radar objects are hidden, or are detected at unexpected distances, or may appear with apparent cross-sections and speeds much different than their actual values.

Keywords: Lidar, refractivity, ducting, evaporation

1. REFRACTIVE EFFECTS AND DUCTING

Radar beam propagation conditions depend upon the refractive environment and are strongly modified when an evaporation duct, or elevated duct are present. The key elements defining an evaporation duct are the temperature and relative humidity as well as their respective gradients. Today the measurements of the evaporation duct are made at the surface of the water and at the height of the deck of a ship; these two points are then used in a curve fitting technique and interpreted using the Monin-Obukhov similarity theorem. This technique is used to infer the gradients in both moisture content and temperature; however, a more accurate representation would be obtained using continuous profiles of both parameters. Techniques using balloons and kites along with surface based buoy measurements have been used in the marine surface layer [1]. Elevated ducts are usually detected using rawinsonde balloon profiles.

Currently, the vertical profiles of both temperature and water vapor are obtained from balloon sondes. The sondes are launched periodically to obtain the vertical profiles. However, local winds as well as pressure gradients cause the balloon to drift and may result in a flawed profile of the region. The balloon has a limited minimum height and will not always locate the evaporation duct because the balloon is released from the height of the shipdeck and the first several seconds of the balloon data are not reliable. Measures of the index of refraction of the air have become the standard way to describe the ducting phenomenon. When the index of refraction of air decreases rapidly enough with altitude the trapping condition is met and a duct is formed. Figure 1 shows four different conditions of radio wave propagation.

The current techniques for retrieving the RF-refractivity rely on point measurements using surface sensors or balloon soundings for characterizing evaporation ducts and elevated refractive layers. These techniques for the evaporative duct suffer from major problems in the case of spatial and temporal resolution. The radiosonde is the most frequently used instrument. It provides satisfactory vertical profiles above about 50 m for humidity, temperature, and pressure. However, its shortcomings include non-continuous measurements, inability to obtain measurements of the evaporative duct, as well as wide area drift, that is the sonde will move with the wind resulting in a profile. While point measurements at or near the surface can provide information on a continuous time scale, they do not help much in

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characterizing conditions aloft. In order to more accurately describe the atmospheric conditions a combination of high spatial and high temporal resolution is necessary. Lidar techniques make it possible to measure water vapor and temperature with sufficiently high spatial and temporal resolution.

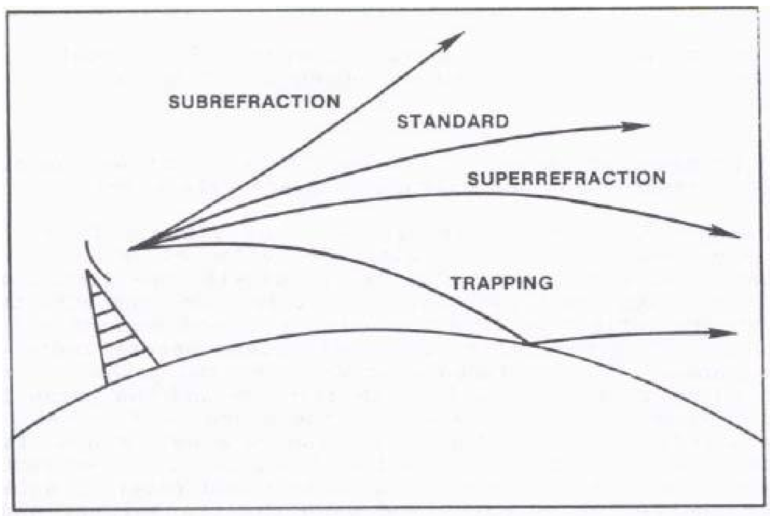

Figure 1. Possible radio wave propagation behaviors, including subrefraction, standard, super-refraction, and trapping (ducting) [2].

The phenomenon of RF ducting is of particular importance when operations are planned that depend on radar beam propagation. RF-ducting is a phenomenon that occurs when the gradients of water vapor and/or neutral density cause a change in the index of refraction of air such that a waveguide is created. This waveguide can be present either at the surface (evaporative duct), or in an elevated layer as shown in Figure 2. Knowing the location and strength of the duct can be used to correct the interpretation of the measured radar signals, for example when a surface duct exists detection can be avoided by flying above the duct in the radar null, this is a tactical change from typically flying in 'below' radar.

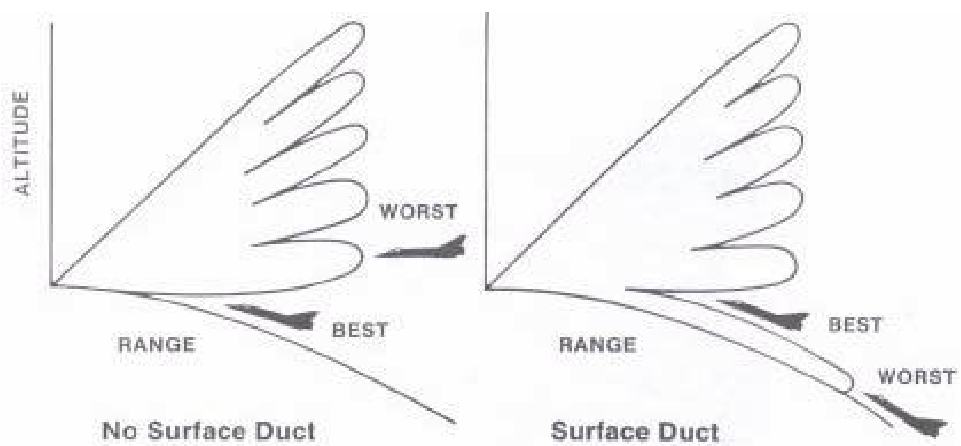

Figure 2. Tactical use of radar coverage [2].

Surface ducting, also known as trapping, is an extreme case of superrefraction. The evaporation duct is a duct found above the oceans surface and is caused by a rapid decrease in humidity with height. RF ducting or trapping occurs when the refractivity decreases with altitude at a rate greater than about –157 N per 1000 meters [3]. Because the index of refraction in air near the surface of the earth typically ranges between 1.00025 to 1.0004, refractivity is conveniently measured in N-units, given by:

$N = (n - 1) * 10^6$,
where n is the index of refraction of air

The value of the index of refraction in the lower atmosphere in N units will generally range from 250 to 400. Through extensive study it has been found that the RF-refractivity in the atmosphere is most strongly affected by the gradients of water vapor. Empirically determined relationships have been found at radio frequencies less than about 50 GHz. Several equivalent forms of the equation have been developed; one form from Helvey [3] is useful for our application,

$N(z) = 77.6\, P(z)/T(z) + 373000\, e(z)/T^2(z)$,
P is the atmospheric pressure in millibars,
T is the temperature in degrees Kelvin,
e is the water vapor pressure in millibars.

Water vapor partial pressure can be found from the measured specific humidity and the atmospheric pressure, which is determined from surface pressure measurements and the hydrostatic equation,

$e(z) = (r(z) * P(z)) / (r(z) + 621.97)$,
e is the water vapor pressure in millibars,
r is the specific humidity in g/kg,
P is the pressure in millibars.

A second more convenient way of describing refractivity is known as modified refractivity (M-units). Modified refractivity has become the standard for measurements because of its simple way of accounting for the Earth's curvature. Whenever the change in M with altitude is negative ($dM/dz < 0$), trapping conditions are present. This is useful for interpreting atmospheric profile plots because trapping layers are immediately obvious when compared to a vertical line in such a diagram [3]. The modified refractivity (M) can be found from N units by accounting for the altitude in question and the curvature of the Earth,

$M(z) = N(z) + (z/a) * 10^6$,
z is the altitude in meters,
a is the radius of curvature of the Earth in meters.

Substituting the Earth's radius of ~6,378,100 m and simplifying yields,
$M(z) \cong N(z) + 0.157z$

2. LIDAR MEASUREMENT AND SIMULATION

An accurate description of the evaporation duct requires high spatial resolution measurements of water vapor and temperature as well as high temporal resolution for the altitude range from the surface to about 100 m. By obtaining these measurements continuously it is possible to see and track changes in the marine surface layer, thereby describing the development and evolution of the evaporation duct. Until recently it has not been possible to obtain high accuracy and high-resolution profiles of water vapor and temperature above the ocean's surface. The near-surface refractivity profiles and evaporation ducts cannot be adequately measured operationally by standard radiosondes, because little useful data is obtained in the first 50 m above the surface, ship contamination of the measurements, and insufficient repetition of the releases [4].

By adapting lidar to work on a near horizontal path it is now possible to make highly resolved temporal and spatial measurements of the atmosphere all the way to the surface of the ocean. This technique creates a volumetric scan of the surrounding atmosphere, and will yield both a vertical distribution as well as horizontal information on the water vapor and temperature. By propagating the lidar system on a near horizontal path it will be possible to yield very high-resolution vertical profile. By assuming that the atmosphere is sufficiently horizontally stratified, that is, the near horizontal paths are sufficiently uniform over ranges from 100 m to 1000 km that the data can be compressed into a single vertical profile with vertical resolutions of less than 0.5 m.

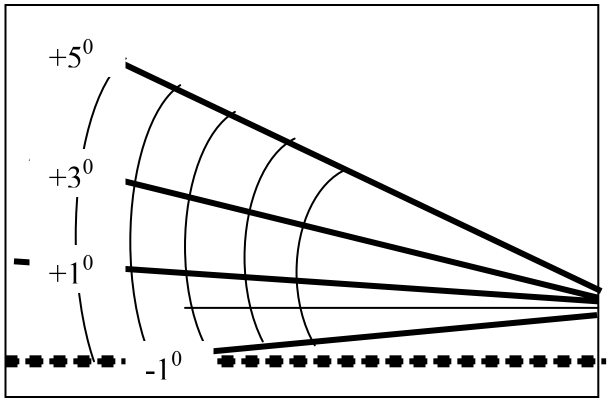

Figure 3. Lidar propagation paths for a volumetric scan of the lower atmosphere.

Penn State University has developed an operational prototype Raman lidar and participated in the design of several other lidar systems. The next system envisioned is the ALAPS or Advanced Lidar Atmospheric Profile Sensor. The ALAPS system will have the capability of measuring on both vertical and horizontal paths and thus allow for a volumetric scan of the atmosphere, see Figure 3. The system will maintain a vertical resolution of 10 m, and when used on a near horizontal paths it will obtain a resolution of approximately 20 cm.

A comprehensive model of the Penn State University lidar system has been developed. The model allows the user to adjust the simulation by choosing laser power, laser repetition rate, atmospheric water vapor, atmospheric temperature as well as time of day. The simulation makes it possible to explore various atmospheric conditions. By utilizing both vertical and horizontal atmospheric paths it will be possible to obtain highly accurate results on radar propagation from the surface through the lower atmosphere. Figures 4 and 5 show the error values expected for water vapor and temperature from the surface to 50 m. These errors were calculated assuming a nighttime operation with 250 mJ per pulse, at a 20 Hz repetition rate and using the 3rd Harmonic of the ND:YAG laser (~355 nm). Figure 6 shows a typical profile of water vapor, temperature and M units for the Persian Gulf on 8/18/2003, notice the change in M units (~60) surrounding the elevated duct.

By utilizing high resolution horizontal lidar it is expected that the errors in the profiles of modified refractivity should be less than 0.25 M units. Because surface ducts typically see changes in the modified refractivity of 10 units or more it will be quite easy to locate and describe them with this level of accuracy.

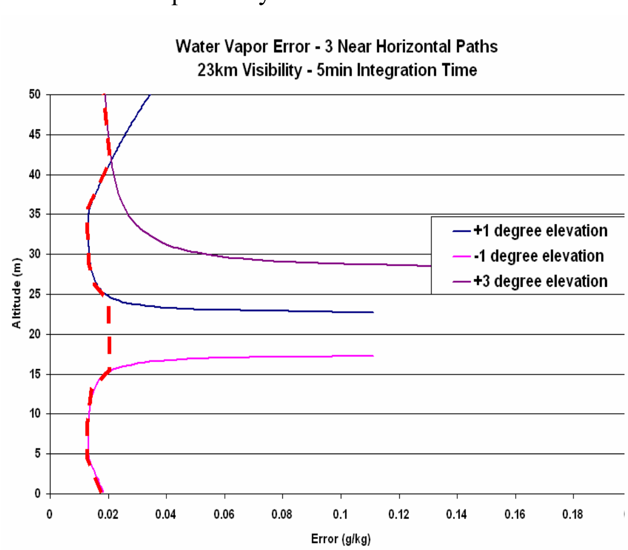

Figure 4. Water vapor

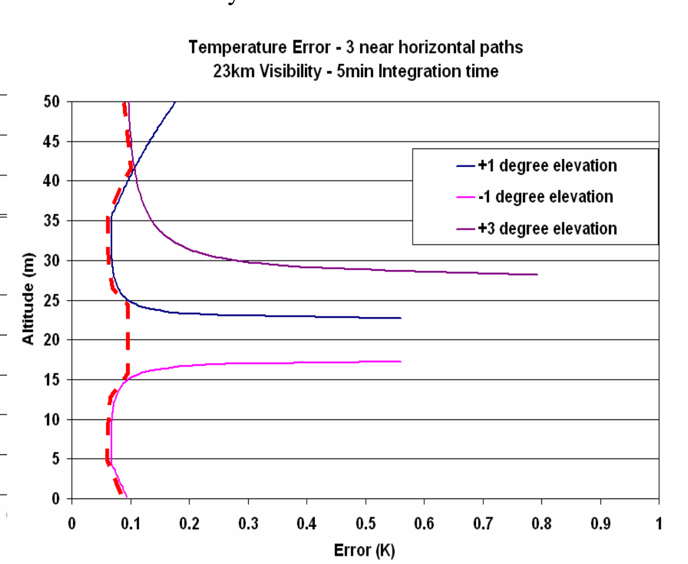

Figure 5. Temperature

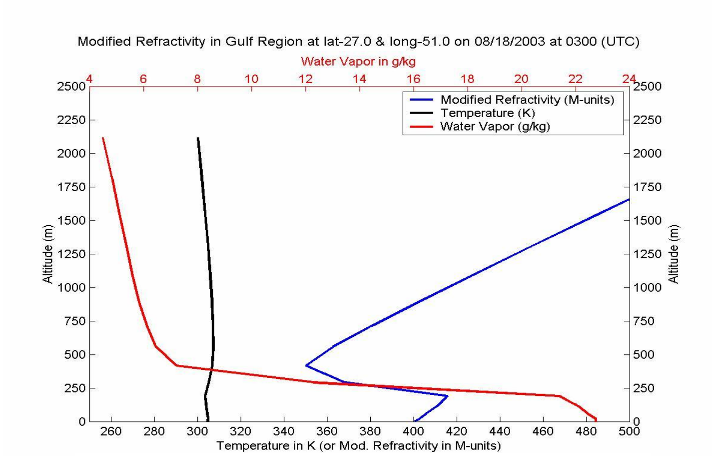

Figure 6. Vertical profile of water vapor, temperature, and modified refractivity [2]. Persian Gulf 8/18/2003

3. SIMULATED SURFACE AND EVAPORATIVE DUCTING

The lidar simulation was used with typical vertical profiles of water vapor and temperature to simulate a surface ducting situation and an evaporation duct. The expected profiles of water vapor and temperature were then calculated to find the expected Raman lidar return signals. The water vapor channel signals are obtained from a profile of specific humidity, and the nitrogen channel signals are obtained from the temperature profile.

3.1 Elevated Surface Duct

The water vapor and temperature profile shown in Figure 6 were used along with other profiles from the Persian gulf to generate the time sequence of refractivity shown Figure 7. The water vapor and temperature profiles were input into the lidar simulation software. The Raman lidar returns were then analyzed yielding a time sequence of the elevated duct shown in Figure 7. The duct can be seen where the decrease in refractivity occurs, starting at an altitude of approximately 250 and continuing to decrease up to 500 m.

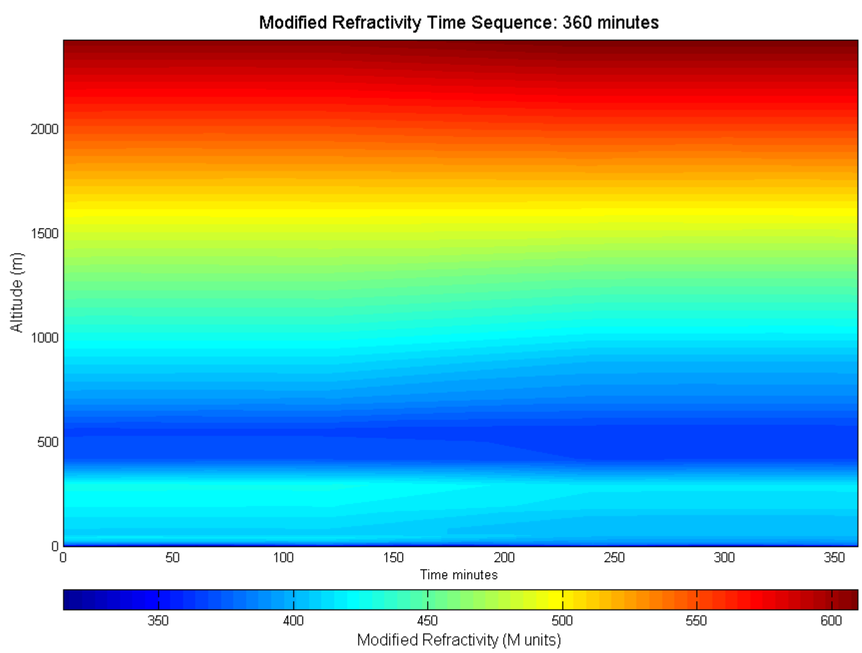

Figure 7. Time sequence of elevated surface duct; Persian Gulf 8/18/2003

3.2 Evaporation Duct

Figure 8 shows an integrated sequence of four profiles describing an evaporation using data taken from off the coast of Oahu, Hawaii [1]. The temperature and water vapor profiles were measured using surface based buoy measurements as well as vertical profiling through the use of a point sensor package suspended from a kite. The kite was raised and lowered multiple times obtaining multiple profiles of the water vapor and temperature. By interpreting these data into the lidar simulation it is possible to model the photon returns and create a time sequence of the evaporation duct. The water vapor profile associated with the last few minutes of the time sequence is shown in Figure 9. The duct can be seen right from the surface as an immediate decrease in M units, which continue to decrease until approximately 30 m in altitude. This sharp decrease from approximately 380 M at the surface to 360 M at 30 m is a typical change for an evaporative ducting situation.

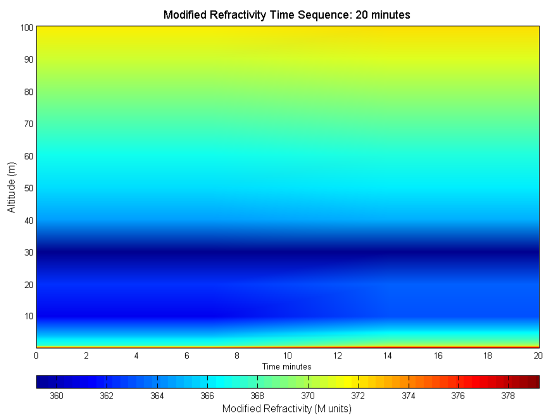

Figure 8. Evaporation Duct

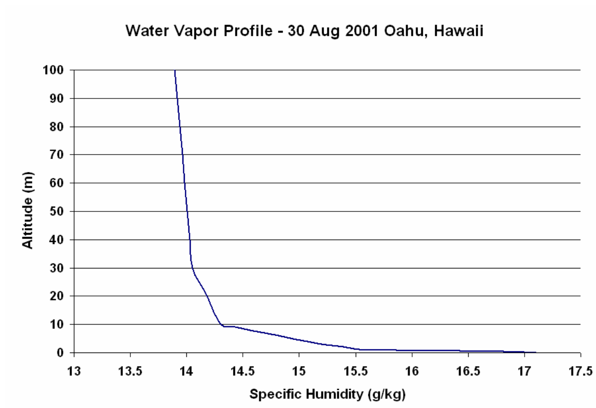

Figure 9. Water Vapor Profile

4. PERSIAN GULF DATA

Water vapor and temperature profiles measured in the Persian Gulf on 8/18/2004 from 0300 UTC to 2100 UTC were input into the lidar simulation software. The data was taken from four different sonde profiles and the times between the sondes were interpolated in order to yield a higher temporal resolution. The result of this makes it possible to obtain the development and location of an elevated duct. Figure 10 shows the water vapor and temperature profiles as well as the resulting profile of modified refractivity in the Persian Gulf on 8/18/2003 [5]. The time sequence of the modified refractivity shown in Figure 11 is of particular interest. At the start of the time sequence the duct is located at approximately 500 m above the surface and later the duct begins to weaken (500 minutes) and slowly builds again. At the end of the sequence there is a strong surface duct at 200 m above the surface with a more significant thickness. Figures 12 and 13 are output from the Radio Physical Optics model. The model utilizes the atmospheric conditions that were measured and uses a ray optics approach as well as parabolic equation techniques to simulate the atmospheric path for radar signals. Figure 12 shows the radar coverage for the start of the time sequence in Figure 11. The phenomenon at the surface (at the location of the duct) where the radar coverage is skewed and extends outward along the earths surface is particularly noticeable. The radar coverage shown in Figure 13 is for average atmospheric conditions and is taken from the U.S. Standard Atmosphere.

5. CONCLUSIONS

By utilizing real world data it is possible to simulate high-resolution water vapor and temperature measurements of the lower atmosphere. Today through the use of radiosondes it is not possible to track the development and evolution of the refractive conditions, primarily because the sondes are released to infrequently. However, by using a lidar in coastal or marine conditions, it will be possible to take high temporal and spatial resolution measurements of the surrounding atmosphere, thus gaining a true understanding of the surrounding refractive conditions. By processing the Raman lidar returns in real time along with the increase in temporal and spatial resolution it will be possible to track and predict the lower atmospheric refractive conditions. The high resolution profiles of the water vapor and temperature can then be utilized to construct a time sequence profile of refractivity. The refractivity is then used to describe the radar propagation and ducting conditions.

6. REFERENCES

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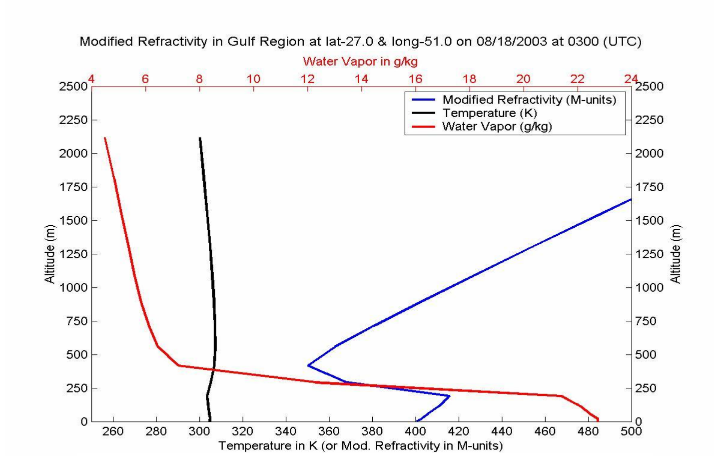

Figure 10. Vertical profile of water vapor, temperature, and modified refractivity [5]. Persian Gulf 8/18/2003

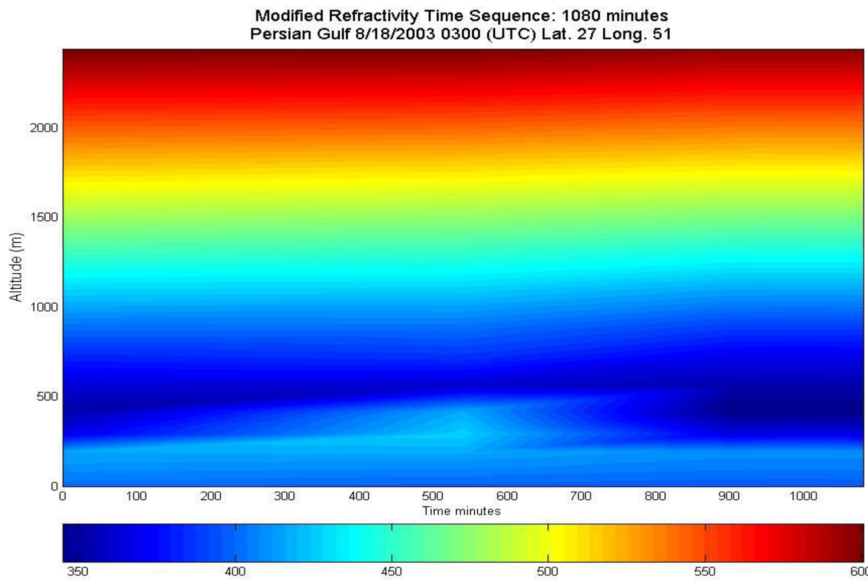

Figure 11. Modified refractivity in the Persian Gulf showing an elevated duct.

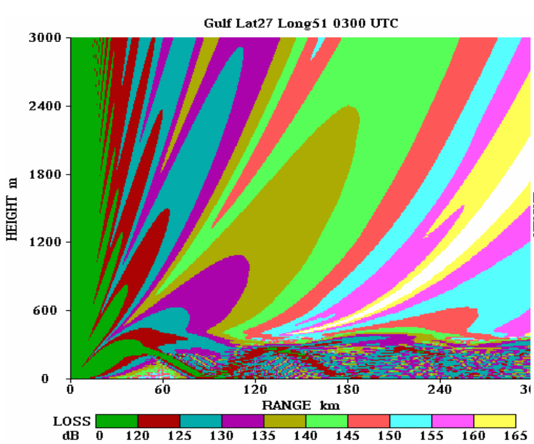

Figure 12 Radar coverage in Persian Gulf

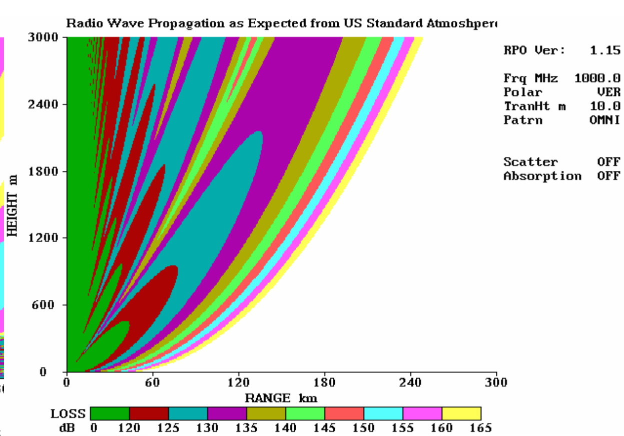

Figure 13 Typical radar coverage from U.S. Standard