Lidar Simulation and Investigation 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, yielding extremely high vertical resolution. 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 similar to an optical fiber. The duct bends and reflects the radar beam along a path effectively trapping it and guiding it over long distances. This is a major problem for the NAVY, because radar propagation paths are skewed in both littoral and open ocean environments. Moreover, ducting skews details of radar returns such that radar objects are hidden, are detected at unexpected distances or may appear with cross-sections and speeds much different than their actual values.**

1. REFRACTIVE EFFECTS AND DUCTING

To describe the radar beam propagation the evaporation duct must be located and quantified. The key elements defining an evaporation duct are the temperature and relative humidity as well as their respective gradients. Today these measurements 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.

Currently the vertical profiles of both temperature and water vapor are obtained from balloon sondes. The sondes are launched periodically and travel upwards obtaining the vertical profile. However, due to winds as well as pressure gradients the balloon does not travel in a purely vertical manner. This drift can skew measurements and may result in a flawed profile of the region. The balloon has a limited minimum height and will not always see the evaporation duct at low elevations, since the balloon is released from the height of the deck and the first several seconds of the balloon flight do not provide reliable data. RF-refractivity which is a measure of the index of refraction of the air, has become the standard way to describe the ducting phenomenon. When the index of refraction of air decreases rapidly enough with altitude a trapping condition is met and a duct is formed. Shown in Figure 1 are four different conditions with which radio wave propagation may follow.

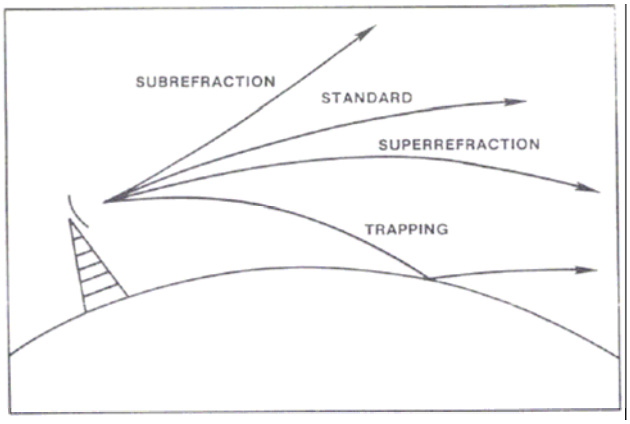

Figure 1. Possible radio wave propagation behaviors, including subrefraction, standard, super-refraction, and trapping (ducting) [1].

As stated above the current techniques for retrieving the RF-refractivity rely on either point measurements at the surface or single balloon soundings for elevated refractive layers. These techniques for the evaporative duct suffer from major problems; spatial and temporal resolution. The radiosonde is the most frequently used instrument, and it provides satisfactory vertical profiles above 50 m of humidity, temperature, and pressure. However, its shortcomings include non-continuous measurements, not obtaining measurements of the evaporative duct, as well as vertical drift, that is the sonde will move with the wind resulting in a drift profile. On the other hand, point measurements at or near the surface can provide information on a continuous time scale but they will certainly lack in vertical information. In order to more accurately describe the atmospheric conditions a combination of high spatial and high temporal resolution is necessary. Lidar techniques now make it possible to measure water vapor and temperature with sufficiently high spatial and temporal resolution.

The phenomenon of RF ducting is of particular importance to the Navy. When military operations are planned it is of crucial importance to know how radar beams propagate. 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 at an elevated location as shown in Figure 2. Knowing the location and strength of the duct or waveguide will yield a great tactical advantage, 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.

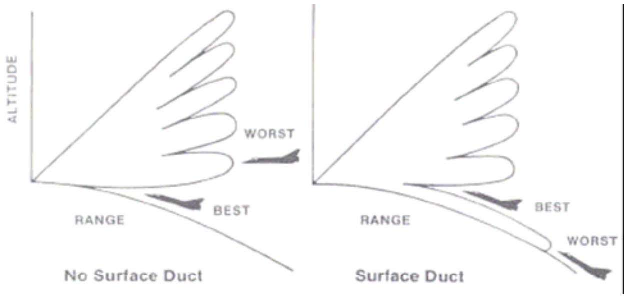

Figure 2. Tactical use of radar coverage [1].

Surface ducting also known as trapping, is an extreme case of superrefraction. Figure 1 shows four possible propagation paths for the radio waves. The evaporation duct is a duct found above the oceans surface and is caused by the 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 [1]. 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

From the above equation N units will generally range from 250 to 400. Through extensive study it has been found that the RF-refractivity in the atmosphere is mostly affected by the gradients of water vapor, temperature and pressure.

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 [2] is useful for our application,

$$N(z) = 77.6\, P(z)/T(z) + 373000\, e(z)/T(z)^2,$$

P is the atmospheric pressure in millibars,
T is the temperature in degrees Kelvin,
e is the water vapor pressure in millibars.

Water vapor pressure can be found from the specific humidity and atmospheric pressure,

$$e(z) = (r(z) * P(z)) / (r(z) + 621.97),$$

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 looking at refractivity is known as modified refractivity (M-units). Modified refractivity has become the standard for measurements because of its simplification in 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 in relation to the critical condition, which appears compared to a vertical line in such a diagram [1]. The modified refractivity (M) can be found from N units by accounting for the altitude in question and the curvature of the earth. M units are simply N units corrected for 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

To accurately describe the evaporation duct it is necessary to have high spatial resolution measurements of water vapor and temperature as well as high temporal resolution for the altitude range from the surface to the range of 50-100 m. By maintaining these measurements continuously it is possible to see and track changes in the marine surface layer, thereby describing the creation 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 radiosondes, due to problems such as lack of data all the way down to the surface, ship contamination of the measurements, and insufficient temporal resolution [3].

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 a horizontal distribution of 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 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.

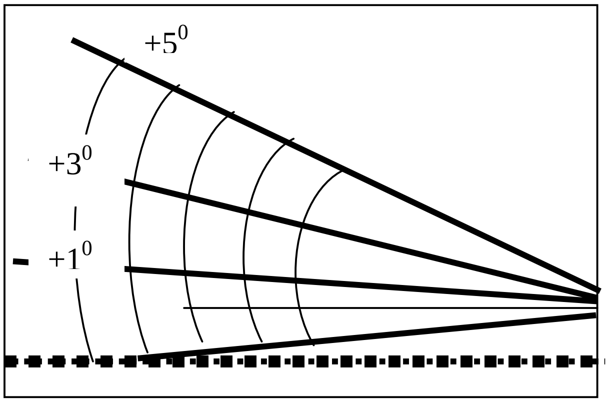

Figure 3. Lidar propagation paths for a volumetric scan of the lower atmosphere.

Penn State University has aided in the development of many operational 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 a vertical and horizontal path allowing for a volumetric scan of the atmosphere as seen in Figure 3. The system will maintain a vertical resolution of 10 m, and when applied to near horizontal paths will realize even finer vertical resolution of approximately 20 cm.

A comprehensive model of the Penn State lidar system has been developed. The model allows for 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 different atmospheric paths above the horizontal it will be possible to maintain highly accurate results from the surface through the lower atmosphere. Shown in Figures 4 and 5 are 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, 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.

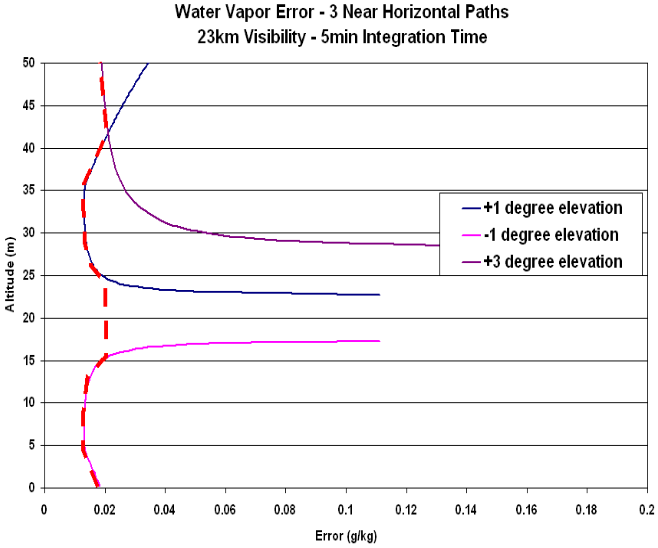

Figure 4. Water vapor error

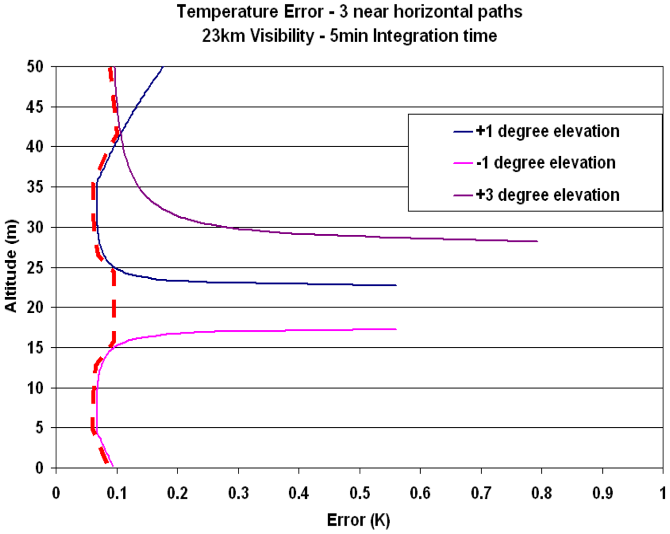

Figure 5. Temperature error

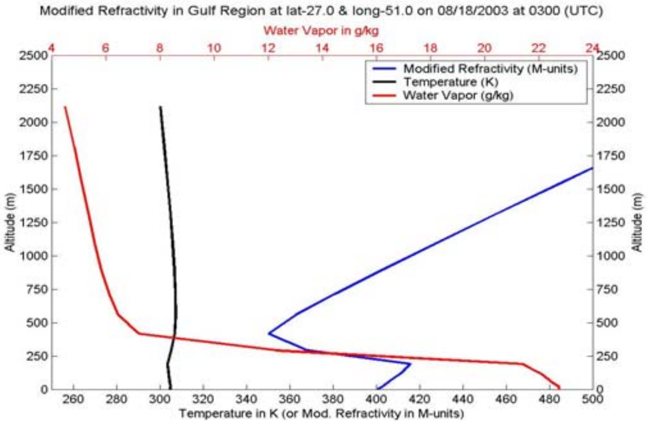

Figure 6. Vertical profile of water vapor, temperature, and modified refractivity [2].

3. SIMULATED SURFACE DUCTING

The lidar simulation was used with vertical profiles of water vapor and temperature in an effort to simulate a surface ducting situation. By assimilating different profiles of temperature and water vapor in the model it was possible to simulate a surface duct. The different profiles of water vapor and temperature were then retrieved using the Raman return signals. The signals from the water vapor channel yielded a profile of specific humidity, and signals from the nitrogen channel yielded the temperature profile. The water vapor profile shown in Figure 7 was adapted from a typical surface ducting situation with high water vapor concentrations at the surface and a large decrease in water vapor with altitude. The temperature profile used was the U.S. Standard Atmosphere. The returns from the Lidar simulation were then processed, yielding a time sequence of the evaporative duct shown in figure 8. The duct is initially quite deep, with the modified refractivity decreasing from 10 m to 70 m, however as time passes the duct appears to weaken and becomes more confined to the area between 40 and 70 m in altitude.

4. PERSIAN GULF DATA

Data taken from the Persian Gulf was assimilated into the lidar simulation program. The data was taken from four different sonde profiles and shows the development and location of an elevated duct. Figure 6 shows the water vapor and temperature profiles as well as the resulting profile of modified refractivity in the Persian Gulf on 8/18/2003 [4].

Of particular interest is the time sequence of the modified refractivity shown in Figure 9. At the start of the time sequence the duct is located at approximately 500m above the surface and as time goes by the duct begins to weaken (500minutes) and slowly builds again. At the end of the sequence there is a strong surface duct at 200m above the surface with a more significant thickness. Figures 10 and 11 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 10 shows the radar coverage for the start of the time sequence in Figure 9. Most noticeably is the phenomenon at the surface (at the location of the duct) where the radar coverage is skewed and extends outward along the earths surface. The radar coverage shown in Figure 11 is for typical atmospheric conditions taken from the U.S. Standard atmosphere.

5. CONCLUSIONS

A comprehensive lidar simulation has been developed at Penn State University. By utilizing real world data it is possible to yield high-resolution water vapor and temperature measurements of the evaporation duct in the lower atmosphere. The profiles of the water vapor and temperature can then be utilized to construct time sequence profiles of refractivity. The refractivity is then used to describe the radar propagation and ducting conditions. By taking measurements on a continuous time scale it is not only possible to detect the duct but also possible to track the evolution of the duct throughout a battlespace environment.

6. REFERENCES

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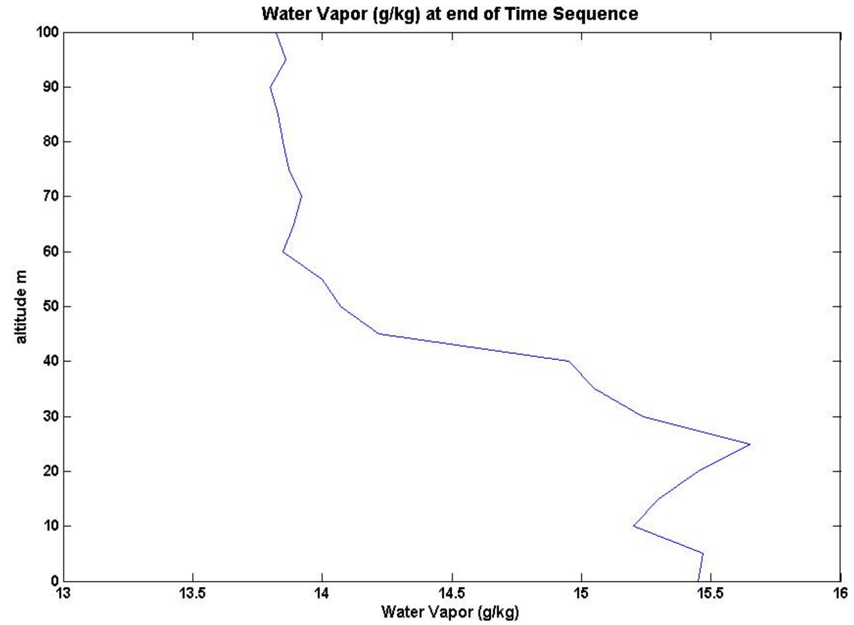

Figure 7. Water vapor profile at 600th minute of time sequence in figure 8.

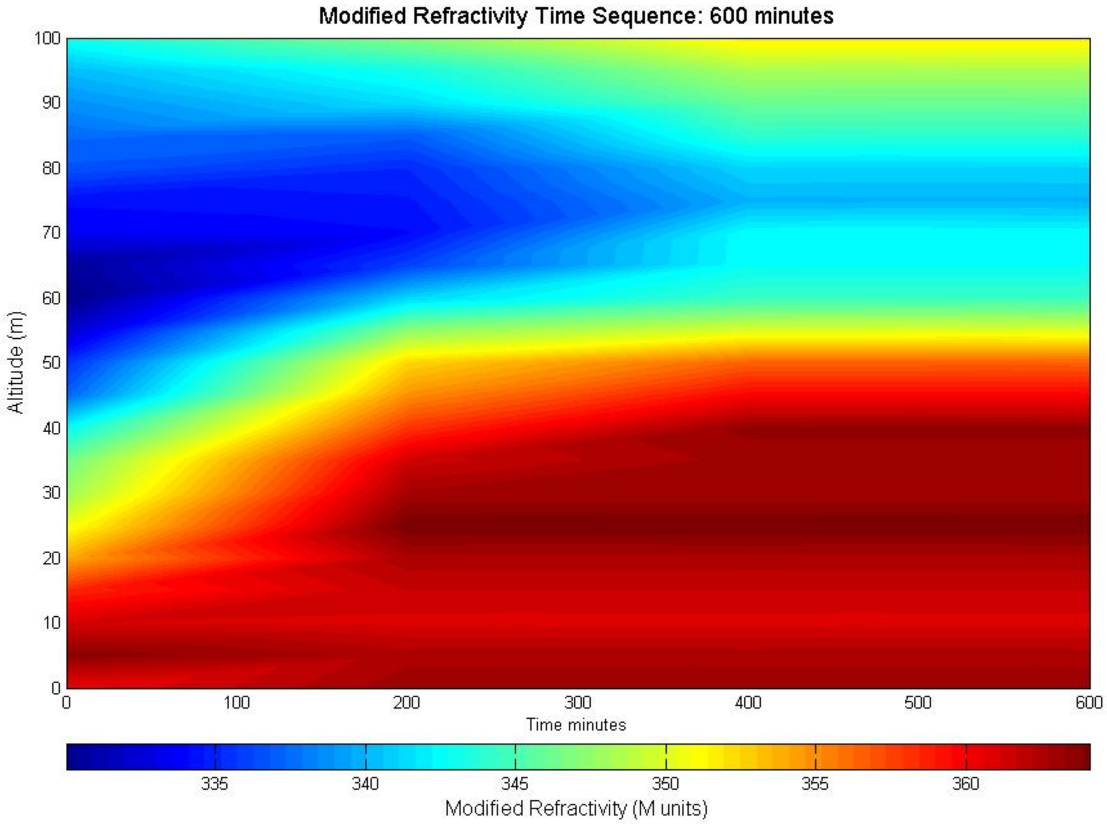

Figure 8. Time sequence of simulated evaporation duct

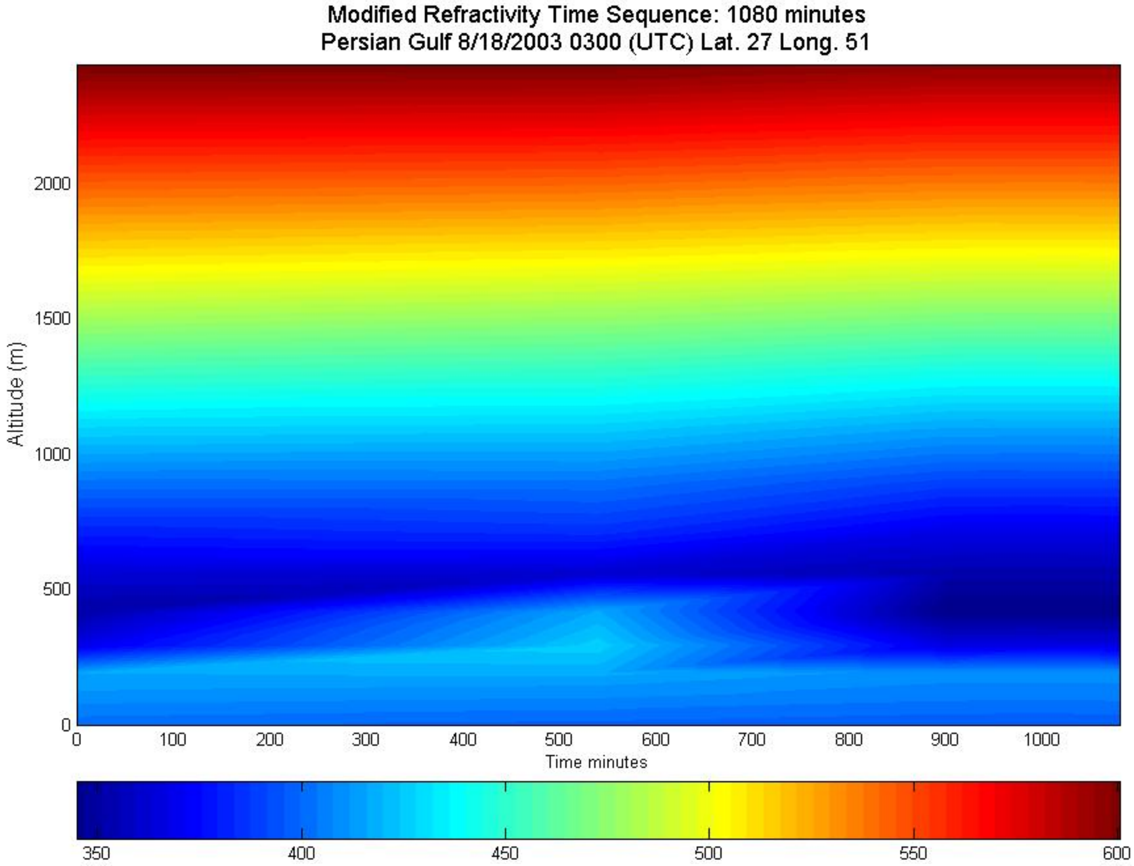

Figure 9. Modified refractivity in the Persian Gulf showing an elevated duct.

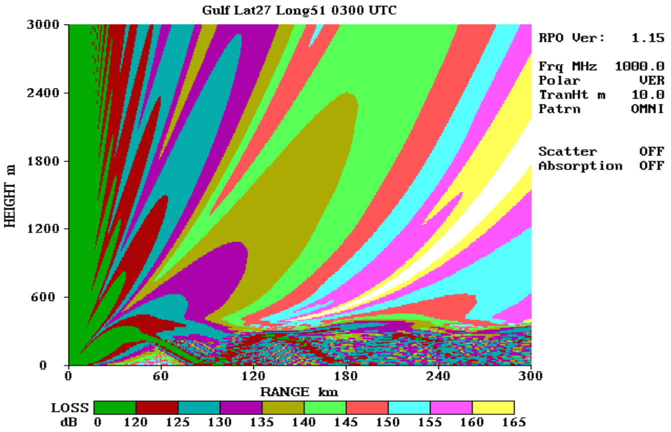

Figure 10. Radar coverage in Persian Gulf

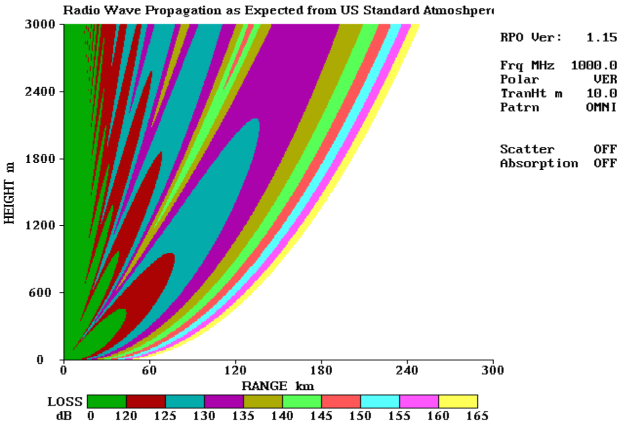

Figure 11. Typical radar coverage from U.S. Standard Atmosphere