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EFFECTS OF ATMOSPHERIC REFRACTION ON LONG-RANGE, NEAR-SURFACE, ELECTRO-OPTICAL SENSING OVER WATER

Ernest Bauer

January 1996

19960802 006

Prepared for
Defense Advanced Research Projects Agency

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Contract DASW01 94 C 0054
DARPA Assignment A-180

PREFACE

This document was prepared in partial fulfillment of a task on Infrared Clutter Characterization and Modeling.

I wish to thank Doug Crowder, NSWC, and Jeff Nicoll, IDA, for presenting the problem to me and making available experimental data from NSWC/Dahlgren at Wallops Island. In addition, a number of people have helped through discussion, in particular Art Aikin and Bob Fraser, NASA/GSFC; Bohdan Balko, IDA/STD; Owen Cote and Edmond Dewan, USAF/PL-GPAA; Andy Goroch, NRL/Marine Met/MRY; Waldemar Lehn, U. Manitoba; Don Snyder, ARL; Ned Stone, NRL/DC; and Klaus Weickman, NOAA/Boulder. This document has been reviewed by Bernie Paiewonsky, IDA, Ned Stone, NRL, and J.W. Trahan, NSWC, Dahlgren, Virginia.

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1. INTRODUCTION TO THE PROBLEM

Modern electro-optical sensors are much more sensitive than the human eye, so they can detect a target much farther away than a human observer can. However, these sensors look through a long optical path in the atmosphere—in excess of 10 kilometers over water—and properties of the atmosphere that normally do not affect human seeing can be important. The optical phase change associated with the refraction correction provided by eyeglasses, say 2 mm of glass, is equivalent to a 0.3 percent change in density (or a 1 °C change in temperature) of 1 km of air. Eyeglasses are used to see objects about 100–200 m away, while modern electro-optical sensors look for targets up to 10–20 km distant. Thus, we now see that the normal variability of the atmosphere can produce significant refractive effects.

Let us discuss the refraction problem for visible wavelengths.[1] In this spectral range, the refractive index n of air is 1.00029 (i.e., only slightly different from that for vacuum, as compared with representative values 1.33 for water and 1.57 for glass). For air it is customary to introduce a *Refractive Modulus*,

$$N = (n - 1) \times 10^6 \quad , \tag{1}$$

and one may introduce the *Optical Phase Change ΔEik* relative to vacuum for a geometrical path length x,

$$\Delta Eik = (2\pi x/\lambda)\,(n - 1) \quad . \tag{2}$$

For orientation, consider an optical telescope located at a height h ~ 3000 m viewing a star at angular elevation θ above the horizon.[2] This sees the star through an air mass

$$M_{tel}(h) = \int_h^\infty \rho(s)\, ds/ \cos\theta \equiv \rho\,(h)\, H/ \cos\theta \tag{3}$$

---

1 In the IR the wavelength is different by a factor of 4–20, the refractive index is slightly different, and especially at wavelengths greater than 4 μm one can also see a target by its own thermal emission rather than by the scattering of sunlight. The present discussion can be applied to the IR. In the microwave (radar) region the atmospheric physics is different because atmospheric moisture plays a big role with evaporation ducts, etc. See Section 4 below.

2 Most modern astronomical observatories are located on mountain tops to minimize refraction and (light and air) pollution effects.

where s = distance along the optical path, $\rho(h)$ = ambient density at height h, and $H = kT/Mg \cong 7$ km; this assumes an approximately isothermal atmosphere. This may be compared with the air mass $M_{sl}(x)$ corresponding to a shipborne IRST viewing path of length x at the sea surface:

$$M_{sl}(x) = \rho\,(0)\,x \quad . \tag{4}$$

Now, if x = 20 km, h = 3000 m, and = 30°,

$$M_{sl}(x)/M_{tel}(h) = [\rho\,(0)/\rho\,(h)]\,[x \cos\theta/H] = 1.35 * [20 * 0.866/7]$$
$$= 3.33 \quad .$$

In other words, the air mass for a shipborne IRST path is significantly greater than that for a telescope looking out to space.

Figure 1 shows the structure including diurnal variability of the *Atmospheric Boundary Layer* (ABL) over land. The ABL is roughly the lowest 10 percent of the atmosphere, the region that shows a strong diurnal variation in temperature profile as a result of solar heating of the ground and subsequent heating of the atmosphere by re-radiation in the infrared. Over land at mid-latitudes a typical day-night temperature difference is 10 °C, as compared with 0.3 °C over water (on account of the very large heat capacity of water as compared to land)[3]; there is still an effect, however, although over water a variety of dynamic effects[4] are more significant than the static variation discussed here.

Why should we care about this? The refractive effects discussed here can lead to a difference in target visual detection range by a factor two or more, and can also give rise to mirages, which may produce time-varying multiple images of a single target. Some of these effects are discussed further below. Figure 2 is taken from a video of NSWC/ Dahlgren experimental work on which Trahan's 1995 paper is based, and shows how the actual image seen varied with time on one particular occasion. The five images shown in Fig. 2 are selected from a video of ~ 45 minutes to display the variety of images seen. This kind of variation could confuse an automated sensor that is not programmed for the effect.

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3 Note that in a desert environment, where the low moisture content of the ground gives a relatively small heat capacity, the day-night temperature difference may be in excess of 20 °C.

4 Associated perhaps with frontal passages, offshore winds, ocean currents, or other phenomena.

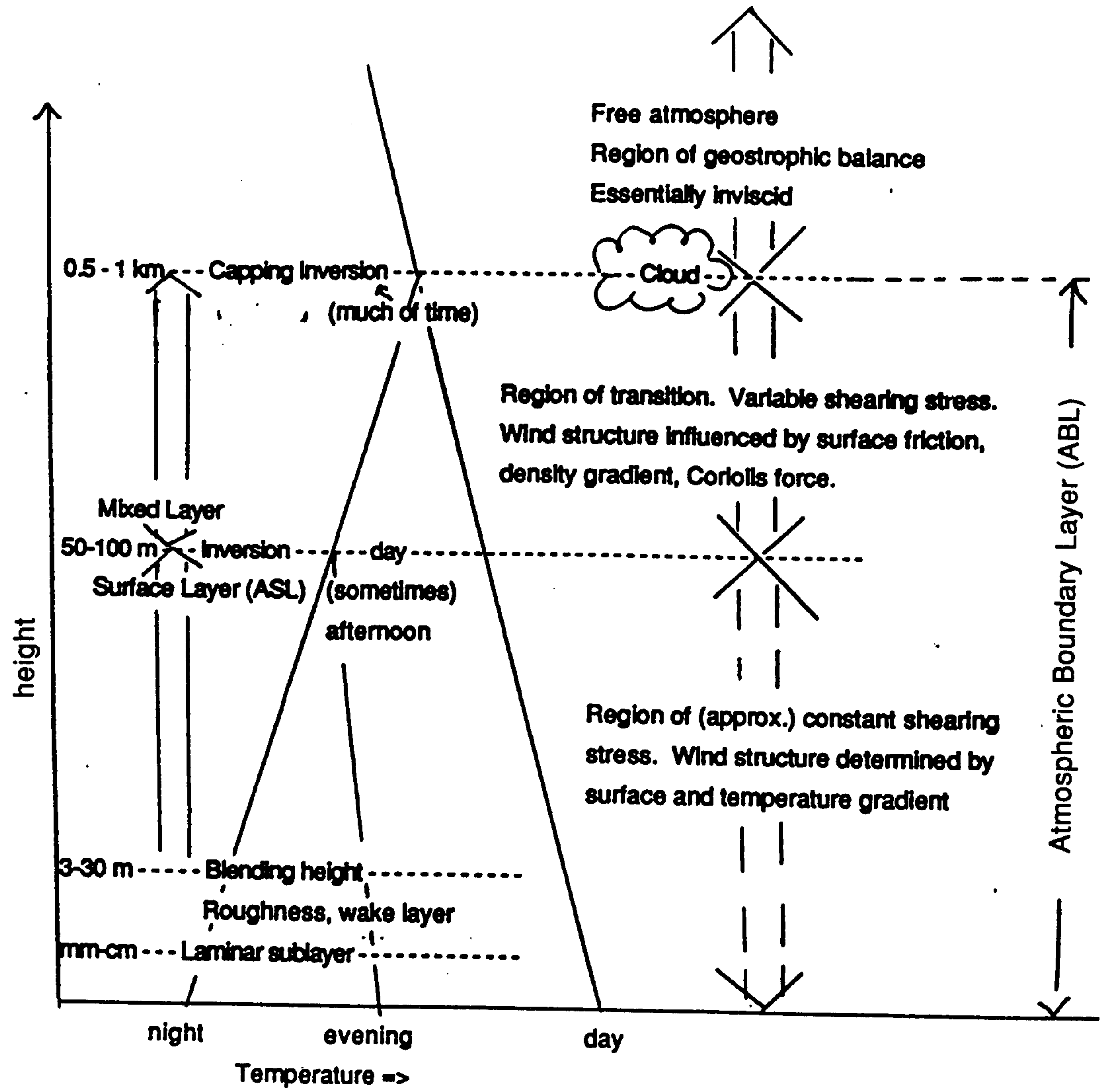

Figure 1. Structure of the Atmospheric Boundary Layer (ABL) Over Land. Schematic.

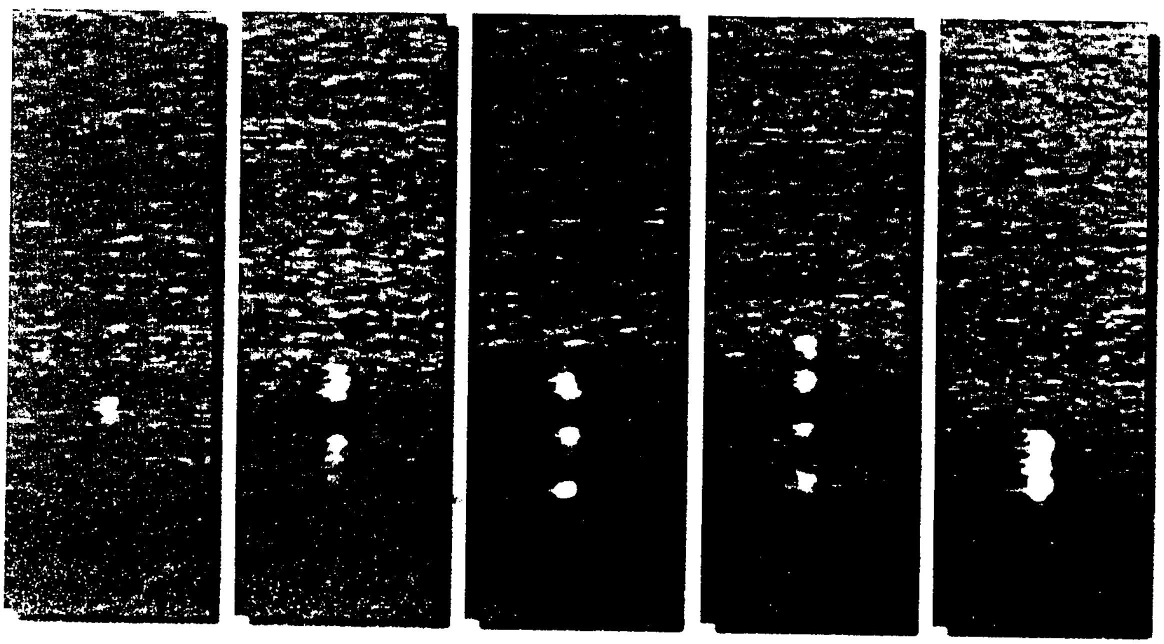

Figure 2. Time-Varying Long-Range Over-Water Observations of a Single Target May Show Multiple (Mirage) Images. (Prepared from data obtained by NSWC/Dahlgren under the HISS program)

2. THE CONCEPT OF ATMOSPHERIC STABILITY: TEMPERATURE AND DENSITY PROFILES IN THE ATMOSPHERIC SURFACE LAYER (ASL)[5]

Figure 1 shows the Atmospheric Boundary Layer (ABL), which is typically about 0.5–1 km thick. We are particularly interested in the lowest 10 percent of this layer, say 50–100 m, the Atmospheric Surface Layer (ASL), which is the portion of the atmosphere in which we live and operate. Evidently, the diurnal and other variation observed in the ABL as a whole will be enhanced considerably in the ASL, which is immediately next to the surface of the Earth where the temperature (hence, the density and refraction) shows its largest diurnal variation.

We see from Fig. 1 that the atmospheric temperature normally changes with height. There are two distinct cases:

- If warm air overlies cold air, the atmosphere is *stable*, in that if an air parcel is displaced vertically it tends to return to its initial position.
- If cold air overlies warm air, the atmosphere is *unstable*, subject to convective overturning.

Stability is defined as a function of the vertical temperature profile, $\partial T/\partial z$, or of the (negative) lapse rate. The lapse rate is defined as $-\partial\theta/\partial z$, where θ is the potential temperature

$$\theta = T(p_o/p)^{R/C_p} \quad . \tag{5}$$

Here p_o is a reference pressure (typically 1000 mb), p is the actual pressure at the height considered; $R/C_p = 0.286$, and θ is conserved during the adiabatic vertical displacement of an air parcel. Now $\partial\theta/\partial z = 0$ for neutral conditions, $\partial\theta/\partial z < 0$ for unstable, and $\partial\theta/\partial z > 0$ for stable conditions.

---

5 Stull, 1991, points out that stability and lapse rate should be defined between two definite altitudes, z_1 and z_2; in other words, it depends on the corresponding temperatures T_1 and T_2 rather than on details of the variation in temperature between z_1 and z_2.

Table 1 characterizes stability in terms of different values of the lapse rate, where we distinguish between three different cases:

- *Lapse Conditions:* If the temperature falls sufficiently rapidly with increasing altitude, then an air parcel which is displaced adiabatically runs away. Its situation is *unstable.*
- *Inversion Conditions:* If the temperature increases with altitude, then an air parcel that is displaced adiabatically from its initial position returns to its initial position. Its situation is *stable.*
- *Neutral Condition:* Between these cases, if the temperature falls off slowly, at the *adiabatic lapse rate* $\gamma_{ad} \sim 6\text{–}10$ °C/km, an air parcel stays wherever it is put.

Table 1. Atmospheric Stability

- Different vertical temperature profiles—$\partial T/\partial z$—correspond to different weather conditions and to different propagation conditions.
- For a quantitative discussion of atmospheric stability, it is appropriate to replace temperature T by potential temperature $\theta = T(p_o/p)^{R/C_p}$, which is constant for a reversible adiabatic (isentropic) condition. (p = pressure, p_o = reference pressure (1,000 mb). Thus one replaces $\partial T/\partial z$ by $\partial\theta/\partial z$; $\partial T/\partial z = -\gamma_{ad} = 6\text{–}10$ °C/km corresponds to $\partial\theta/\partial z = 0$.
- *"Lapse"*: Here potential temperature falls off with increasing altitude, so that $\partial\theta/\partial z < 0$. If an air parcel is now displaced vertically,[a] it runs away—*unstable* conditions.
- *"Inversion"*: Here temperature increases with increasing altitude, i.e., $\partial\theta/\partial z > 0$. If an air parcel is displaced vertically, it returns to its original position—*stable*.
- *"Neutral"*: The crossover between lapse and inversion. In fact, this corresponds to $\partial\theta/\partial z = 0$ so that $-\partial T/\partial z$ = "adiabatic lapse rate." Here a displaced air parcel simply stays where it is put.

Type	Characteristics	Frequency (%)			
		on Land (U.S.)[b]		over Ocean (Bermuda)[c]	
		Summer	Winter	Summer	Winter
Unstable	Day, bright sun, convection	35	12	25	50
Neutral	Cloudy, windy	30	48	70	47
Stable	Night, low wind, little cloud	36	40	0	3

a Adiabatically, i.e., without gaining or losing energy.

b 10 U.S. stations (Doty et al., 1976).

c Data from Weather Ship Echo (45° W, 35° N); but note that data from WS Bravo (50° W, 57° N) in the Labrador Basin are quite different, with a very high frequency of very unstable conditions (ASTD < − 3 °C in winter), while WS Charlie (35° W, 53° N) in the Newfoundland Basin, 1,720 km away, gives mainly neutral conditions (ASTD ~ 0 °C, especially in summer). From Dion and Leclerc, 1990.

Table 1 also correlates stability with weather (insolation, wind, cloud) conditions and presents the relative frequency of different conditions both at 10 U.S. land stations,[6] and over some oceanic stations.[7] Note that Table 1 is an extremely condensed and over-simplified discussion of stability (for more detail see, e.g., Turner, 1970 or a variety of textbooks on air pollution meteorology and tracer dispersion).

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6 From Doty et al., 1976. A great deal of work on atmospheric stability over land was done in the 1960's and early 1970's in the context of air pollution, since the spreading of pollutants is affected significantly by the level of atmospheric stability (see, e.g., Turner, 1970).

7 There is a limited amount of work on stability over the oceans, based largely on observations using weather ships (see, e.g., Dion and Leclerc, 1990).

3. REFRACTION OVER WATER: VISUAL RANGE

Table 2 presents atmospheric and refractive conditions over water. It is customary to quote the (measured and recorded) air-sea temperature difference (ASTD)

$$ASTD = T(air) - T(sea) \tag{6}$$

correlating stable and unstable conditions with positive and negative values of ASTD.[8]

Table 2. Refractive Effects Over Water

Stability:	Unstable "Lapse"	Neutral "Lapse"	Stable "Inversion"
ASTD = T(air) – T(water)	< 0	~ 0	> 0
Weather	Day, sun	Cloudy, windy	Night: clear, calm
Convection?	Much	Some	Little
Refractive Effects[a]			
Condition	Sub-refractive	Normal	Super-refractive
Horizon Range	Decreased	Nominal	Increased
Example[b]: (km)	19	26	41
Model Prediction	Good	Fair	Poor
Mirage: Type	Inferior/Desert	None	Superior/Arctic
Frequency	Common	--	"Uncommon" [c]

[a] See, e.g., Paulus, 1991.

[b] From Trahan, 1995.

[c] But note that superior mirages occur under stable meteorology which predominates at night over land, when optical observations are not normally made. Note that IR observations can be made at night, so that IR mirages are likely to be common at night, at least over land. I do not know how this applies to conditions over the ocean.

One may ask how ASTD values are obtained. From about the time of World War II into the 1970's there were a number of weather ships on the oceans, mainly in the North Atlantic and the North Pacific (see, e.g., Roll, 1965, p. 15), and they measured T(air) at deck or mast level and T(sea) either by scooping a bucket of water from the sea and

[8] Cf. Dion and Leclerc, 1990, and Trahan, 1995.

measuring its temperature or by reading the temperature of the sea water that enters the condenser intake of the ship.[9]

There is a limited amount of work on stability over the oceans, based largely on observations from weather ships; such ships provide much more information than previous sources, which were largely merchant ships only passing through a particular region. Nowadays we get a great deal of data from weather satellites, but they of course give much less detail on near-surface effects than do near-surface observations. Note that the day-night difference in stability conditions over water is unlikely to be large, but the influence of air masses and frontal passages may well be particularly important.[10]

- In general, at mid- to high latitudes the atmosphere over the eastern side of the oceans is stable with low-level inversions; note the stable layer of stratus clouds off the California coast. By contrast, air over the western side of the oceans is very unstable in winter, with cold masses coming off the continents of Asia and America producing a deep, unstable mixed layer. In between, over the broad ocean there is a transitional zone.
- In the North Pacific there are lots of storms with mechanical mixing,[11] with strong mixing on both sides of the storm track.
- The character of the air masses will vary strongly near the continent-ocean boundaries, but this variability will be less critical in the open ocean, except in the storm tracks of extra-tropical cyclones.
- Note that a great deal of data from the weather ships is available (e.g., at NOAA), which has apparently not been analyzed.[12]

To summarize:

- When the atmospheric lapse rate is unstable, the high-altitude density is *large* (because T decreases with height), thus light rays are bent *up*, and thus the visual range is *reduced*[13] (relative to "normal" or *neutral* conditions).

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9 Some 2 m below the surface. Cf. Roll, 1965, Chapter 2.

10 When warm air passes over cold water, there will tend to be fog, while if cold air moves over warm water there is likely to be a cloud deck; but below this cloud deck the lapse rate is likely to be more unstable than on the average.

11 Turbulent mixing can be driven either by temperature gradients or by wind shears. Here we are talking about the effects of wind shears.

12 A great deal of these data are presented in the *U.S. Navy Marine Climatic Atlas of the World*, Naval Weather Service Detachment, Asheville, North Carolina, March 1978. These are large volumes that are frequently discarded by libraries on the grounds that they exist at DTIC in microfiche; in fact, the fine detail is lost in the poor quality of the DTIC record.

13 This is significant primarily over the ocean with its uniform surface; over land there tend to be hills and valleys so the relatively small effects of refraction are obscured by larger, geometrical factors.

- When the atmospheric lapse rate is *stable*, the high-altitude density is relatively *small* (because T increases), thus light rays are bent *down* and the visual range is *increased*.[14]
- When the atmospheric lapse rate is *neutral*, the temperature gradient lies in the range of – 6 to – 10 °K/km (respectively, the dry and saturated adiabatic lapse rate of air) and quasi-horizontal light rays in such an atmosphere are slightly curved, being concave down with a radius of curvature of about 40,000 km, as a result of the atmospheric pressure gradient due to the Earth's gravitational field.

14 For an example of this, see the discussion of the "Mysterious Marfa Lights" in Section 5 below.

4. REFRACTION OVER WATER: MIRAGES

When the refractive effects discussed above are sufficiently large, they may give rise to mirages. Mirages are multiple images (sometimes inverted) that arise when a given target is observed through two (or more) different optical paths between target and observer. Figure 3 shows several different kinds of mirages. Note that:

- When the atmospheric density *increases* with altitude, there is produced an *inferior*[15] mirage; this is also known as a *desert* mirage because it is frequently observed in strongly sunlit deserts.
- When the density *decreases* sufficiently rapidly with altitude, there is produced a *superior* mirage; this is also known as an *arctic* mirage because it is frequently observed at high latitudes.
- With a *variable* profile of density with altitude, there can be complex mirages known as *fata morgana*.

Thus, combining the discussion of lapse rate as a function of stability with that of mirages as a function of density gradient (which, of course, is a function of the lapse rate), we see that:

- When the lapse rate is *unstable*, so that the high altitude density is (relatively) *large*, there could occur *inferior* or *desert* mirages.
- When the lapse rate is *stable*, so that the high altitude density is low, there could occur *superior* or *arctic* mirages.
- When the lapse rate is *neutral*, there will *not* be any mirages.

Figure 2 shows multiple images that are presumably due to such density or temperature gradients. Table 2 summarizes refractive effects over water under unstable, neutral, or stable conditions.

For orientation on the horizon ranges shown in Table 2, Table 3 gives the range to the horizon as a function of viewing height without considering the effects of refraction. This permits some kind of scaling of the numerical values given in Table 2.

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15 "Inferior" and "superior" describe the vertical displacement of the image from the original object (Frazier and Mach, 1976).

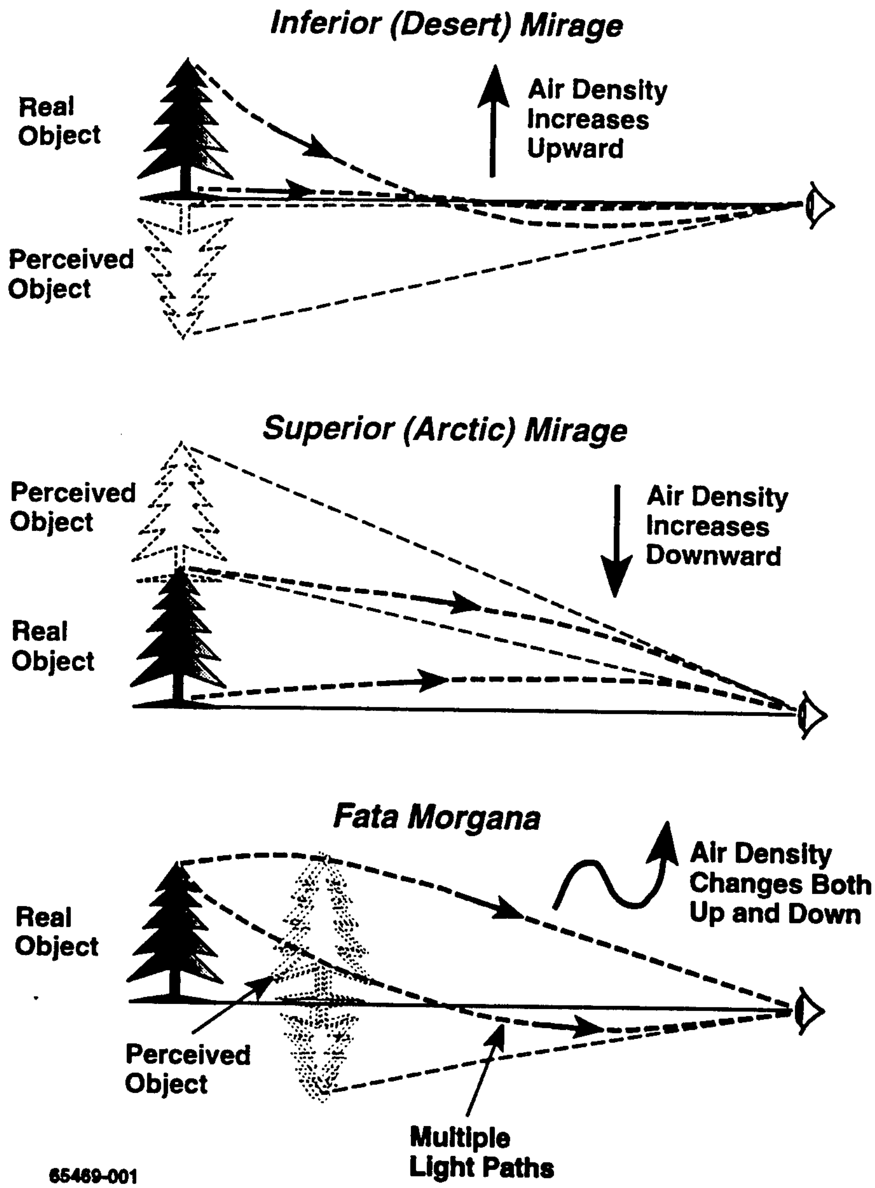

Figure 3. How Mirages Are Produced (from Davis, 1982)

Table 3. Range to Horizon Without Considering Refraction

Height of Sensor (m)	1	2	5	10	30	50
Range (km)	3.8	5.6	8.6	12.2	21.2	27.3

5. DISCUSSION

From an operational standpoint, dynamical and coastal variations in detection range and in mirages (such as multiple images) are likely to be particularly important. Table 4 lists some "typical" examples:

- Mirages are "not uncommon" in (near-coastal) ship-to-ship, ship-to-shore, and shore-to-ship viewing. (See, e.g., Minnaert, 1993, esp. Chapters 3 and 4).
- When warm winds blow over a cold ocean, mirages have been observed [see, e.g., Gossard, 1982; Richter et al., 1979 (who discuss U.S. West Coast effects, presumably under "Santa Ana" conditions); Trahan, 1995 (who reports observations off the East Coast)]. These are all near-coastal (10–30 km offshore) rather than broad ocean observations. The current NSWC work has very good time resolution (~ 1/30 sec) and shows significant variations, presumably due to variations in the wind over various (geographic or thermal) obstacles on shore.[16] Figure 2 is taken from a video of the NSWC/Dahlgren experimental work on which Trahan's paper is based and shows how the actual image seen changed with time on a particular occasion.
- It is well known that microwave radars suffer from anomalous "evaporation duct" propagation effects (see Brocks, 1964; Ko et al., 1983). The physics here is somewhat different from visible and IR propagation, because the microwave refractive index varies strongly with atmospheric humidity, so that the presence or variability of atmospheric moisture can lead to a variety of propagation effects.
- The relation of ASTD to atmospheric stability in the ASL may not be a very firm one.
- I believe—but do not yet have any data—that with the exception of weather-front passages the mirage phenomena at least are generally a near-coastal rather than a broad ocean phenomenon.

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16 One possible effect of mirages is that at long range several images (typically aligned in a vertical plane) may be seen from a single target. At sufficiently short range the images may all merge, causing the mirages to disappear, but this could be too late for effective action to be taken. It is also possible that atmospheric gravity waves can produce some effects (see Lehn et al., 1994), but these effects are unlikely to be very important.

Table 4. Some Applications and Open Questions

1. Refraction effects can lead to significant variations (factor 2) in visual ranges. These effects are most striking over the ocean where there are no mountains or other geographical obstacles.
2. Mirages are "not uncommon" in shore-to-ship, ship-to-shore, and other near-coastal viewing.
3. When warm winds blow from land over cold oceans, mirages are "not uncommon."
   - Richter et al., 1979; Gossard, 1982; Trahan, 1995.
   - NSWC have good time resolution, find short-time variations; see Fig. 2.
4. On land there are severe mirage effects over sunlit deserts. (There might be very different effects at night because of large diurnal variations in temperature, stability, and consequent mirage effects.)
5. Microwave radars have anomalous "evaporation duct" propagation effects. The physics is different from the optical/IR range where refraction is due to total atmospheric density, while atmospheric moisture is important for refraction in the microwave frequency range.
6. There may be some questions on the relation of ASTD [Air-Sea-Temperature Difference, see Eq. (6)] to atmospheric stability. ASTD is generally measured over a 10–20 m altitude interval, while atmospheric stability refers to the Atmospheric Surface Layer, or the lowest 100–150 m.
7. It seems likely but not yet established that anomalous refraction and multiple images due to mirage effects generally will occur in near-coastal situations but not over the open ocean.

- Note that there are also severe mirage effects over sunlit deserts, when the near-surface temperature may be 100 times the adiabatic lapse rate.[17] This has implications for wire-guided and other such surface-to-surface missiles.
- A related refractive effect observed over land at night is the "Mysterious Marfa Lights" phenomenon observed from a highway just east of Marfa, Texas (a small town west of Big Bend National Park). Looking in a generally westerly direction at night over the desert one sees lights that appear and disappear. Presumably what happens is the following: at night the land cools much more rapidly than the ABL, giving rise to stable refractive conditions so that light rays are bent down, giving a greater visual range than in the daytime. The lights are likely car lights on the Marfa-to-Presidio highway. In the direction in which the lights are usually seen, that highway passes through the Shafter area, and it loses some 1,500 to 2,000 feet of elevation in 8–10 miles. Parts of the road are steep and winding so that cars coming toward Marfa would be almost certain to have their headlights aimed slightly upward and in the

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17 See, e.g., Geiger, 1965, p. 77 ff. Discussion taken from Brock's work; a "familiar instance is when one walks to a sunny sand beach and finds, on taking off one's shoes, that the sand is "burning hot" even though the ambient temperature at 1–2 m is not unduly high. (In this context, note that some desert plants have leaves set on top of a very tall stalk, presumably because photosynthesis functions better under the more equable temperature at 1–2 m elevation rather than at the more extreme conditions near the ground.)

direction of the Marfa lights viewing area (about 30 miles away) at several places along the road.[18]

[18] I am indebted to Prof. J.D. Corbin, Department of Physics, Sul Ross State University, Alpine, Texas, for this detailed description.

6. SOME OPERATIONAL IMPLICATIONS FOR SHIP SELF-DEFENSE

The refractive effect discussed here has only been discovered quite recently, and it is not yet clear where and how frequently it occurs. Thus any discussion of operational implications depends on the frequency of occurrence of "anomalous" refractive effects at different locations, which requires detailed meteorological investigation. Off the west coast of North America (Southern California) "Santa Ana" conditions occur perhaps 4–10 days per year. Off the east coast of North America where (westerly) winds from the land are prevalent, such effects are likely to be observed frequently in spring or summer, when the land is significantly warmer than the ocean.[19] At other geographical locations, and at different seasons (and at different times of day) the frequency of occurrence will be different.

Operationally these refraction effects could be masked or dominated by turbulence (see Takken et al., 1995).

Meteorological measurements on shipboard can determine the temperature profile on a ship, e.g., by comparing the temperature at the top of a mast with that on the deck, which would presumably be similar to the profile on shore; appropriate measurement techniques have to be developed and used to provide a meteorological data base for the effect.

If meteorological conditions are favorable for atmospheric optical anomalies, there are likely to be multiple images jumping up and down in a vertical plane. We know that at sufficiently short range the various images merge into a single image of a real target. If the range at which the images merge is long enough to permit a successful launch and intercept, the existence of multiple images is not itself critical. However, if the images merge at insufficient range, then clearly the EO target detection system will fail in its

[19] Note that there is a diurnal variation between offshore breezes in the daytime and onshore breezes at night, the "well-known" sea breeze/land breeze phenomenon.

interception. Whether the effect is sufficiently operationally significant to indicate modification of the system requires more detailed investigation.[20]

[20] Presumably such an investigation is ongoing at NSWC/Dahlgren, but I do not know of its current status or conclusions.

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1. AGENCY USE ONLY ***(Leave blank)***

2. REPORT DATE
January 1996

3. REPORT TYPE AND DATES COVERED
Final—May 1994 to November 1995

4. TITLE AND SUBTITLE
Effects of Atmospheric Refraction on Long-Range, Near Surface, Electro-Optical Sensing Over Water

5. FUNDING NUMBERS
DASW01 94 C 0054
ARPA Assignment A-180

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8. PERFORMING ORGANIZATION REPORT NUMBER
IDA Document D-1815

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Defense Advanced Research Projects Agency
3701 N. Fairfax Drive
Arlingrton, VA 22203-1714

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 180 words)***

Modern electro-optical sensors are much more sensitive than the human eye, so—other things being equal—they can detect a target much farther away than a human observer can. However, such sensors look through a long optical path in the atmosphere and at such distances atmospheric refraction effects can affect sensor viewing. This paper begins with a review of variations in the normal atmospheric temperature profile in the lowest 50–100 m above the surface—the "Atmospheric Surface Layer" (ASL)—pointing out that the horizontal range for target detection can vary, possibly by more than a factor of two. The perception of multiple targets produced by a variety of optical mirage phenomena is also discussed. The purpose of this discussion is to point out new meteorological concepts (developed, largely in the context of air pollution meteorology, in the 1960's) to the electro-optical propagation, and to raise some questions as to the operational significance of refraction that produces multiple images, which the author cannot yet answer.

14. SUBJECT TERMS
Sensor, Atmosphere, Electro-optical sensors, Refraction, Mirages

15. NUMBER OF PAGES
26

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102