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ATMOSPHERIC EFFECTS ON COMMUNICATION AND ELECTRONIC WARFARE SYSTEMS WITHIN TURKEY AND SURROUNDING AREAS

by

Serdar Turk

September 2010

Thesis Advisor: Peter Guest
Second Reader: Karl D. Pfeiffer

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ATMOSPHERIC EFFECTS ON COMMUNICATION AND ELECTRONIC WARFARE SYSTEMS WITHIN TURKEY AND SURROUNDING AREAS

Serdar Turk
Lieutenant, Turkish Air Force
B.S., Turkish Air Force, 2003

Submitted in partial fulfillment of the
requirements for the degree of

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September 2010

Author: Serdar Turk

Approved by: Peter Guest
Thesis Advisor

Karl D. Pfeiffer
Second Reader

Dan C. Boger
Chairman, Department of Information Sciences

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ABSTRACT

This thesis presents the most complete climatology of radio wave (VHF and higher frequencies) tropospheric ducting within Turkey and the surrounding areas ever published. This ducting can result in greatly extended propagation ranges. Atmospheric data from radiosonde upper air observations were collected for a five-year period at stations in Adana, Ankara, Diyarbakir, Isparta, Istanbul, Izmir, Athens, Bucharest, Crete Island, and Tuapse. The upper level and surface ducting yearly average frequencies for these stations were 59.46%, 34.22%, 37.53%, 38.15%, 50.67%, 45.69%, 64.69%, 30.24%, 65.59%, and 21.05%, respectively. Ducts occurred mostly in summer. These frequencies were much higher than previously published climatologies. However, many of these ducts were too shallow to be operationally significant. Atmospheric pressure was correlated with duct heights for some stations, but sometimes the correlation was positive while other times it was negative. In most cases, no correlation was found between duct height and wind speed or direction. Ducts tended to be more common in coastal regions. Regions away from the coast usually have topography limits the effects of the ducts away from the coast, and these inland regions tended to have less ducting occurrence Therefore, these results are most applicable to the coastal regions.

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I. INTRODUCTION

The purpose of this study is to find ducting conditions and to quantify patterns and trends of them within Turkey and surrounding areas, and to understand how ducting can be effective on the performance of communication systems.

> Electronic Warfare (EW) plays an important role in the overall scheme of military strategy. Information superiority plays a vital role in the operation area. A key role of EW is to be able to exploit electromagnetic (EM) missions from a hostile source, turn that information into intelligence on an adversary's order of battle, intentions, and capabilities, and to render communications and weapons systems useless, all while protecting their own system. (Cairns-McFeeters, 1992)

The key matter is how the systems will be used effectively to send and receive signals. Many things can affect the electromagnetic radiation in the earth's atmosphere. The ducting is one of the reasons for the causes of anomalous propagation. Through ducting, radio frequency detection ranges can be extended. Understanding ducting enables one to take advantage of the environment in EW.

> Anomalous propagation occurs frequently and therefore must be factored into any warfare commander's decision-making process. Weather forecasters supporting military operations should understand the effects of atmospheric variables on radio and radar performance. They should collect, analyze, and evaluate available data to describe the existing atmospheric propagation condition and to understand how it will change over time. They should provide radar operators and operational commanders with this information on a timely basis. (Ford, 2005)

Determination of refractive conditions can help to predict the following:

- How far away enemy sensors will be able to detect friendly assets (missiles, aircraft, ships, boats),

- How far away friendly sensors will be able to detect enemy assets, and where reconnaissance platforms need to be placed to exploit the atmosphere and extend friendly detection capability,
- What altitudes provides aircraft with the greatest weapons stand-off range, and
- From what direction friendly assets should approach the enemy to give the greatest detection advantage (Ford, 2005).

This thesis includes an overview of EM propagation through the atmosphere, discussion of environmental factors that affect EM propagation, and finds ducting conditions for ten different locations. It concerns radio waves at VHF and higher frequencies and the space wave mode of transmission.

Atmospheric data was collected from ten different radiosonde stations. The stations examined are located in Adana, Ankara, Diyarbakir, Isparta, Istanbul, Izmir, Athens, Bucharest, Crete Island, and Tuapse. To find refractivity profiles for each radiosonde, a MATLAB program was written. This program reads radiosondes, calculates modified refractivity, finds the first three ducts in the profile if they exist, and finally does some statistics to evaluate the ducting effect on EM propagation.

This thesis adds power to operators and commanders' prediction ability. Knowing how to use the ducting climatology can extend commanders and operators' line of sight. Communication is like breathe: you have never known its importance until it is gone.

II. ELECTROMAGNETIC WAVES AND ATMOSPHERIC PROPAGATION

A. ELECTROMAGNETIC WAVE

Electrons have negative charges and protons have positive charges. If a particle is charged, it produces an electric field in all directions. While particles of the same charge repel, oppositely charged particles attract each other. If the particle moves, the electric field changes. The electrical potential difference between two locations is called voltage.

If a charged particles moves, it creates magnetic field. If an electron moves through in a wire, the magnetic field encircles the wire. Its direction depends on the direction of electron movement. If a charged particle moves, it produces both an electric field (because the particle is charged) and a magnetic field (because the particle is moving). An accelerating charged particle creates an Electromagnetic (EM) wave.

Figure 2 shows the creation of EM waves. The magnetic and electric fields of an electromagnetic wave are perpendicular to each other and to the direction of the wave. The motion of the particle is changing, the electric field is changing and the magnetic field is changing. The changing electric field creates a new magnetic field, and the changing magnetic field produces a new electric field. The collapsing and regeneration of the electric and magnetic fields is what allows EM radiation to propagate (Guest, 2005).

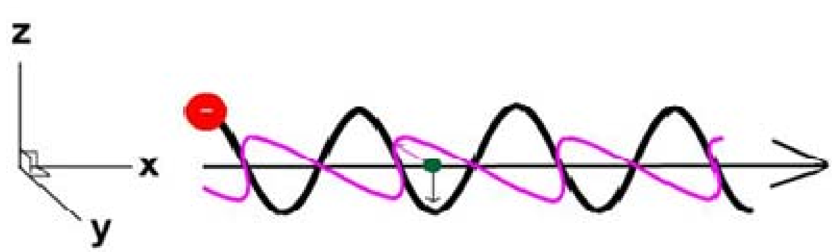

Figure 1. Electromagnetic (EM) Wave Generated by an Accelerating Electron [From (Guest, 2005)]

B. ATMOSPHERIC PROPAGATION

Electromagnetic wave propagation is affected by the properties of the medium located between the transmitting antenna and the receiving antenna. In most situations radio waves in free space travel in straight lines (an exception being gravitational bending as predicted by General Relativity theory), while radio waves traveling within the earth's atmosphere are affected by varying conditions. The influence exerted on radio waves by the earth's atmosphere adds many new factors to complicate what at first seems to be a relatively simple problem. These complications are due to a lack of uniformity within the earth's atmosphere. Atmospheric conditions vary with changes in height, geographical location, and even with changes in time (day, night, season, and year). Knowledge of the composition of the earth's atmosphere is extremely important for understanding wave propagation (Integrated Publishing, 2007).

Electromagnetic radiation (including radio waves) can be reflected, refracted, and diffracted within the atmosphere. To understand radio propagation, it is useful to consider different regions of the atmosphere surrounding the earth as shown in the Figure 2.

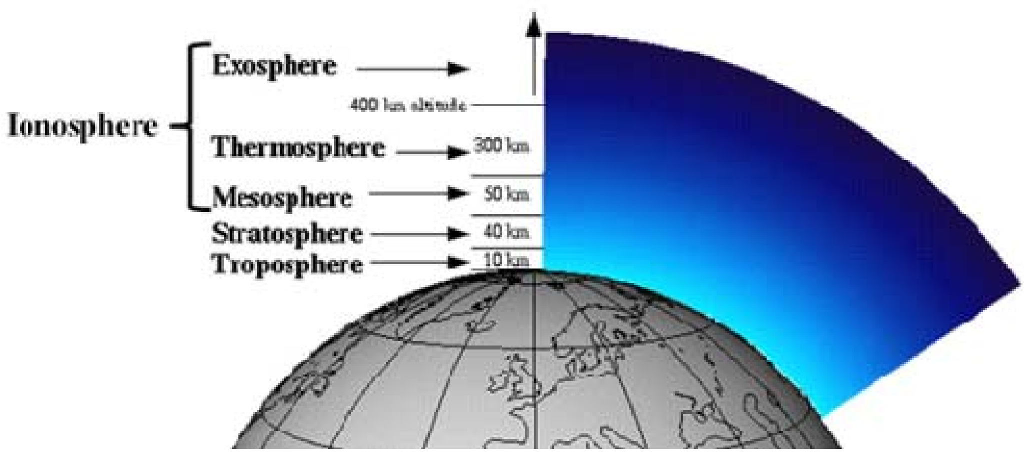

Figure 2. Regions of the atmosphere

Just above the earth's surface is the troposphere, followed by the middle atmosphere (or stratosphere), and finally the ionosphere. The troposphere is characterized by relatively high moisture content and is affected by surface topography. Virtually all weather phenomena take place in the troposphere. The temperature in this region generally decreases with altitude, clouds form, and there may be turbulence due to wind shear or surface heating. Vertical variations in temperature, humidity, density, and pressure in the troposphere can have a substantial effect on the propagation of radio waves. The stratosphere has much more constant conditions and there is little water vapor present. Therefore, the stratosphere has relatively little effect on radio propagation. The ionosphere has charged particles that cause upward propagating radio waves in the HF and lower bands (see Table 1 below) to be refracted back toward the surface. This is the most important region of the atmosphere for long distance point-to-point communications in the HF range (Davidson, 2003). However, this thesis is concerned with tropospheric propagation.

Table 1. Frequency Ranges and Propagation Characteristics for Different Bands

Bands	**Frequency Ranges**	**Propagation Characteristic**
ELF	0.3 - 3 kHz	Earth/ionosphere waveguide modes
VLF	3 - 30 kHz	Earth/ionosphere waveguide modes
LF	30 - 300 kHz	Ground waves (Guided by ground)
MF	0.3 - 3 MHz	Ground waves
HF	3 - 30 MHz	Sky waves (Ionospheric “Reflection”)
VHF	30 - 300 MHz	Space Waves
UHF	0.3 - 3 GHz	Space Waves
SHF	3 - 30 GHz	Space Waves
EHF	30 - 300 GHz	Space Waves

How an EM wave behaves in the atmosphere is usually related to its frequency. Different frequencies behave differently under the same conditions. Table 1 shows frequency ranges and characteristics for different bands. Space waves are usually considered to have "line-of-sight" propagation, but refractive effects can be very important and increase or decrease the line-of-sight ranges.

1. Ground Waves

EM radiation can propagate in various modes of transmission. Ground waves are radio waves that travel near the surface of the earth. The ground wave is actually composed of two separate component waves: surface waves and space waves. A surface wave travels along the surface of the earth. A space wave travels over the surface.

2. Sky Waves

Sky waves are radio waves that are reflected (actually refracted) back to earth from the ionosphere.

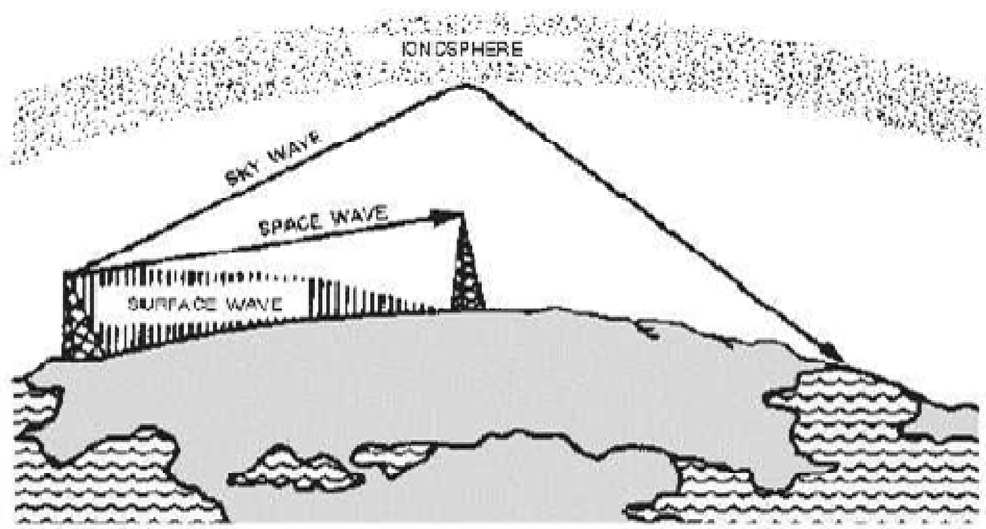

Figure 3. Diagram Showing Ground Waves (Surface and Space) and Sky Waves [From (Davidson, 2003)]

III. ATMOSPHERIC EFFECTS ON PROPAGATION

A. ATMOSPHERIC EFFECTS ON RADAR RANGE

In the atmosphere, electromagnetic waves do not propagate in straight paths as they do in free space. They behave differently depending on the frequency and the atmospheric effects. This thesis concerns radio waves at VHF and higher frequencies and the space wave mode of transmission. In this range, the most important atmospheric effects happen in the troposphere, usually in the lower part near the earth's surface. Space waves in the troposphere undergo attenuation, scattering, and refraction.

For radar transmissions, EM energy must propagate toward a target and then be reflected back toward the antenna. In free space, radar energy propagates according to the simple form of the radar equation (Skolnik, 2001):

$$R_{\max} = \left[\frac{P_t G A_e \sigma}{(4\pi)^2 S_{\min}} \right]^{1/4} . \qquad (3.1)$$

where:

P_t = Transmitted power, W

G = Antenna gain

A_e = Antenna effective aperture, m^2

σ = Radar cross section of the target, m^2

S_{min} = Minimum detectable signal, W.

In the troposphere, this simple form of the radar equation does not adequately predict the range performance of the actual radars. There are several reasons for failure of the simple form of the radar equation. This thesis will focus on those situations where and when the simple radar equation and line-of-sight propagation do not occur due to effects caused by the earth's surface and atmosphere.

Propagation effects might extend the radar range or reduce it. It is important to consider the earth's environment when predicting radar performance. Scattering (reflection off particles and inhomogenieties), refraction (bending), ducting, diffraction, attenuation, external noise and backscatter from land, sea and weather clutter, and attenuation in rain and other hydrometeors modify free space radar performance and affect the EM propagation (Skolnik, 2001).

B. REFRACTION

Unlike free space, the atmosphere is not uniform. Variations in pressure, temperature, and most importantly, humidity, cause electromagnetic waves to be bent (refraction). A bending toward the surface can extend the radar horizon and increases the coverage of the radar, while bending away from the earth will result in decreased ranges. Refraction can also introduce an error in the measurement of the target elevation angle; the apparent position of a detected target is different from its actual position.

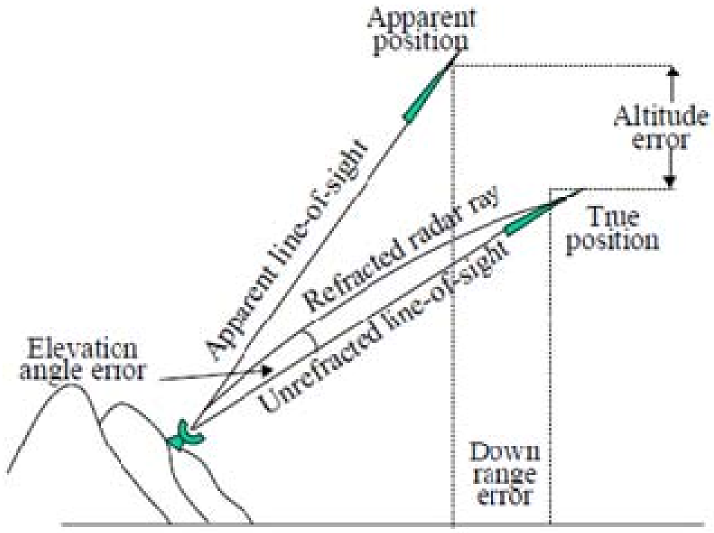

Figure 4. Tracking Errors for Standard Atmosphere [From (Davidson, 2003)]

Refraction of the radar waves in the atmosphere is due to the variation of the velocity of propagation with altitude. The index of refraction (Equation 3.2) is a measure of velocity of propagation in a medium compared to the velocity in free space. EM waves travel faster in mediums with relatively lower indices of refraction. The index of refraction, n, for a particular medium is determined by the magnitude of the phase velocity in space, c, (i.e., the speed of light) divided by the phase speed of light in the medium, v.

$$n = c / v \tag{3.2}$$

At the earth's surface, the value of the index of refraction is around 1.000315. In order to simplify the use of refraction characteristics it is useful to define a quantity called the refractivity, N, which is the index of refraction minus one times 10^6. This results in easy to use numbers (such as 315 instead of 1.000315). The refractivity, N, for radio waves depends on atmospheric pressure, P (hPa), Temperature, T, (K) and vapor pressure, e, (hPa) according to the following formula.

$$N = (n-1)x10^6 = 77.6\frac{P}{T} - 5.6\frac{e}{T} + 3.75x10^5\frac{e}{T^2} \tag{3.3}$$

Note that this formula is valid for all radio frequencies in the VHF or higher frequency ranges. The index of refractivity corresponds to N=315 at sea level.

The vertical gradient of N determines how EM energy will propagate through the atmosphere in relation to the horizontal. If dN/dz (N gradient) is positive, EM energy is bent upward (subrefraction), and if it is negative, EM energy is bent downward.

To identify trapping conditions and determine the occurrence of ducts, it is easy to use a modified index of refraction, M, where z is the height above the surface in meters (Equation 3.4):

$$M(z) = N(z) + 0.157Z \,. \tag{3.4}$$

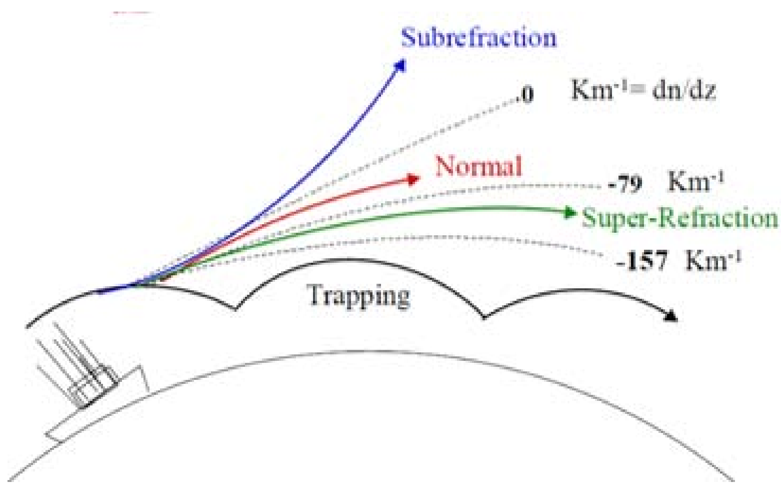

Figure 5. dN/dz and Refraction Categories [From (Davidson, 2003)]

When dM/dz=0, the ray curvature equals the earth's curvature. This is another way of saying that when the N-gradient is -157 units per kilometer, the ray has the same curvature as the earth. M will increase with height in the standard atmosphere. The importance of M is that for a duct to exist, dM/dZ must be negative somewhere in the profile (Davidson, 2003). Figure 5 shows the refraction categories according to the N gradient.

M and N profiles can be compared numerically as shown in Table 2.

Table 2. Comparison of N and M Gradients for Refractive Conditions

Refractive condition	**dN/dz (N units/km)**	**dM/dz (M units/km)**	**Distance to Surface Horizon**
Subrefraction	0 < N	157 < M	Reduced
Normal	-79 < N < 0	78 < M <157	Standard
Superrefraction	-157 < N < -79	0 < M < 78	Increased
Trapping	N < -157	M < 0	Greatly Increased

> A trapping layer is the region where dN/dz < -157 units/km or dM/dz < 0. The ray curvature bends downward relative to the earth. A trapping layer that does not extend down to the surface is sometimes referred to as an elevated layer. A duct is the region associated with the trapping layer; duct EM energy is confined and channeled between the top and bottom of the duct. The top of the duct will always be the top of the trapping layer. However, the bottom of the duct can, and often does, extend below the bottom of the trapping layer. A duct can have its lower boundary at the surface (a "surface based duct") or above the surface (an "elevated duct"). (Davidson, 2003)

Refraction is the bending of radio waves. Unlike reflection, there is no sudden direction change in refraction. The EM wave bends as it passes through regions with different indices of refraction. The index of refraction of a medium changes with the wave's phase velocity.

$$v = \frac{c}{\sqrt{\epsilon_r}} = \frac{c}{n}. \tag{3.5}$$

As seen from Equation 3.5, the velocity of propagation within any medium is a function of the permittivity (dielectric constant) of the medium. The index of refraction, n, is equal to $\sqrt{\epsilon_r}$, where ϵ_r is the relative dielectric constant.

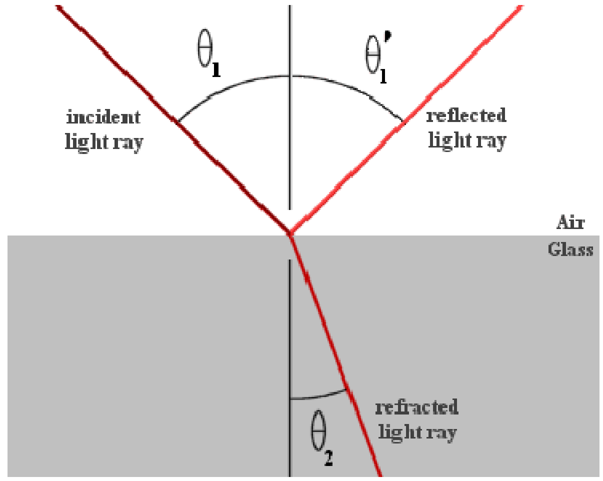

Figure 6. Snell's Law

According to the Snell's Law, when a propagating wave in medium 1 with refractive index n_1 impacts medium 2 with index n_2 at an incidence angle θ_1, the refraction angle θ_2 is given by Equation 3.6 (Davidson, 2003):

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \ . \qquad (3.6)$$

Although in the atmosphere n does not change abruptly, Snell's Law can still be used to predict propagation angles resulting from changes in n. From Snell's Law, it is clear that if the θ_1 is large enough, the critical angle can be exceeded and propagation ray paths are almost parallel to the trapping layer. The largest possible angle of incidence that still results in a refracted ray is called the critical angle; in this case, the refracted ray travels along the boundary between the two media. In addition, the vertical position of a target can be wrong if there is no correction for atmospheric refraction.

C. DUCTING

Normally, in the troposphere, the air is colder at higher elevations. However, sometimes the temperature increases with elevation. When this happens, it is known as a temperature inversion. Temperature inversions are dynamically stable and often prevent the mixing of air by turbulence. This can trap moisture at the lower levels and cause a strong decrease in vapor pressure, e, across the inversion. The increase in temperature and more importantly (for most situations) the associated decrease in vapor pressure (humidity) can cause radio waves to bend toward the earth more sharply than the earth's curvature, and hence the radiation is "trapped" near the surface. This situation associated with inversion creates what are known as channels or ducts, where extended "over-the-horizon" propagation ranges can occur. If any EM wave reaches and enters a duct, this duct acts as a waveguide to send signals long distances. Knowing the ducting climatology of a region is important for any Electronic Warfare System that transmits or receives radio signals (Davidson, 2003).

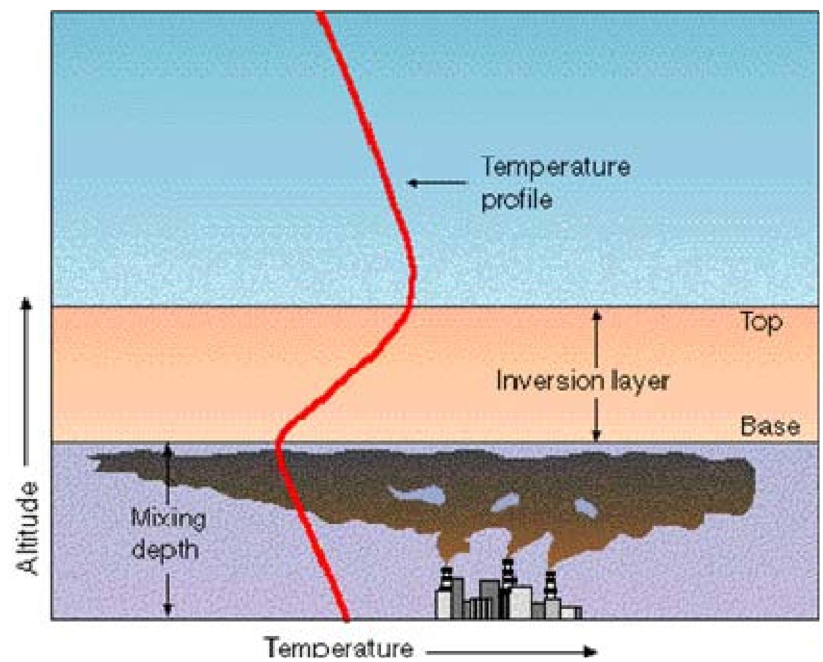

Figure 7. Temperature Inversion [From http://apollo.lsc.vsc.edu/classes/met130]

The gradient of the modified refractivity with height is the best method to see the ducts. Equation 3.3 was about refractivity, N. To identify the trapping conditions modified refractivity is used:

$$M(z) = N(z) + 0.157Z = 77.6\frac{P(z)}{T(z)} - 5.6\frac{e(z)}{T(z)} + 3.75x10^5\frac{e(z)}{T^2(z)} \quad (3.7)$$

P = Atmospheric Pressure in milibar

T = Temperature in Kelvin

e = Vapor Pressure in milibar

Z = Height.

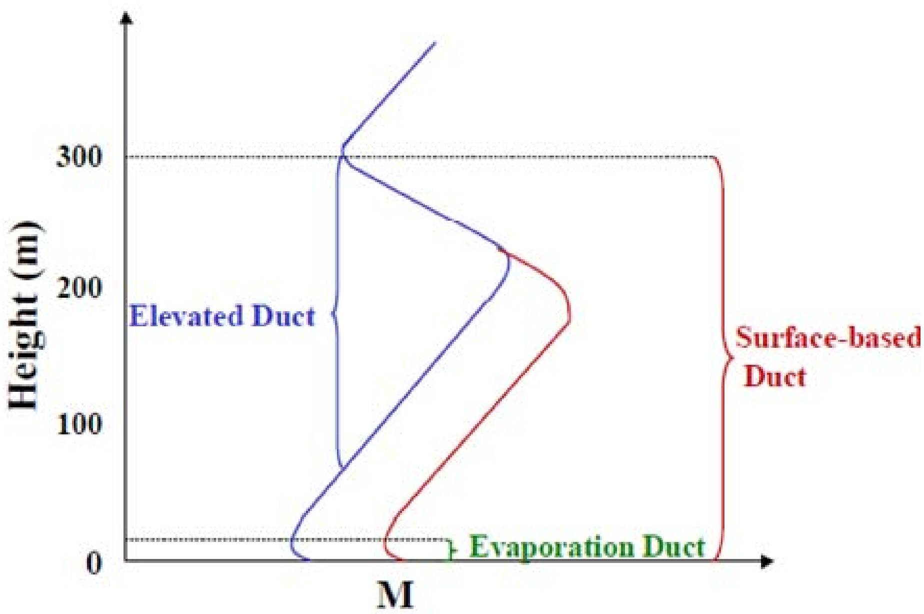

Figure 8. M Relationship for Elevated Trapping Layer and Duct [From (Davidson, 2003)]

Figure 8 shows different types of ducts. The top of the trapping layer is the top of the duct. The bottom of the trapping layer can be determined by drawing a vertical line from the top of the duct down until it crosses the M profile. If it is a surface-based duct, the bottom of the trapping layer is the ground.

1. Evaporation Ducts

Evaporation ducts most commonly occur over the ocean and other large bodies of water. They are found very close to the surface, in the lowest two meters or so. The air right at the surface of a body of water is usually nearly saturated with water vapor, which means that the relative humidity, RH, is 100 percent. Over oceans, salt causes the surface RH to be 98%. Although the relative humidity is high over the sea where the air touches, it usually decreases rapidly in the several meters just above the sea if the upper air is not saturated (i.e., foggy). Because of this rapid decrease in humidity, refractivity also decreases rapidly, enough to refract radio waves back toward the surface. Thus, a low-lying duct traps the EM waves. Signals can propagate along the surface of the water in an evaporative duct. Evaporation ducts can cause the radar ranges for targets at or near the sea surface to be considerably greater than the free space range; although this effect may be counteracted by the increase in surface clutter associated with stronger evaporations ducts (Skolnik, 2001).

Figure 9. Mirage Over the Water Associated with an Evparation Duct [From (Martin, 2007)]

Figure 9 shows an "inferior" mirage caused by an ocean surface that is much warmer than the air. Because warmer water has a relatively higher vapor pressure, this situation is also associated with strong evaporations ducts. These mirages associated with evaporation ducts are best seen during the daytime, though they also occur at night. Evaporative ducts can act as an RF mirror (and sometimes an optical mirror) and reflect signals from the top of the duct (Martin, 2007).

2. Surface-based Ducts

The base of a surface-based duct is at earth's surface. There are three types of surface-based ducts. One of them is the evaporation duct discussed previously. The second one is created from an elevated trapping layer, and the third one is created from a surface-based trapping layer.

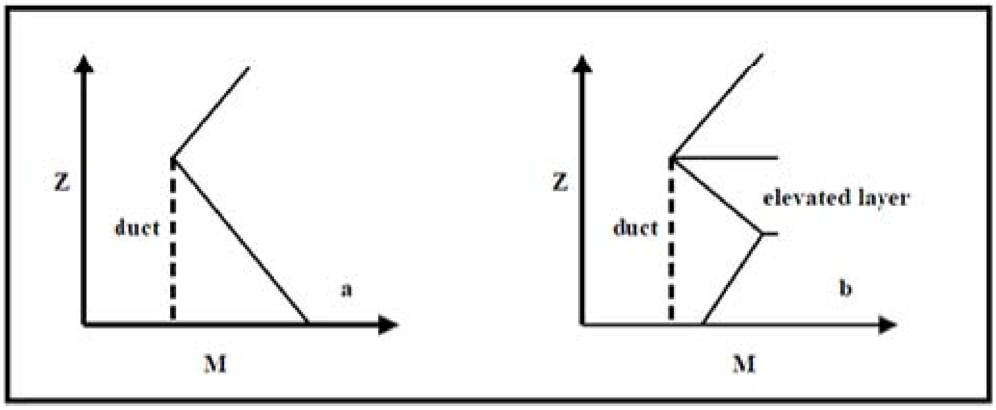

Figure 10. Surface Duct for (a) Surface-based Trapping Layer and (b) Elevated Trapping Layer [From (Davidson, 2003)]

As seen in Figure 10, the value of M at the duct top is less than the value of M at the surface.

Figure 11. Trapped Moisture Over Land Due to Radiational Cooling and Inversion Formation Near the Surface can Create Surface-based Ducts Over Land [From (Martin, 2007)]

3. Elevated Ducts

The base of an elevated duct lies above the surface of the earth. This type of duct is similar to the surface-based duct. The only difference is that the bottom of duct is higher than ground level. This situation is generally caused by temperature inversions or decreases in humidity (vapor pressure) with elevation.

Figure 12. Elevated Inversion with a Base of 620 m is Formed by Subsidence in a High-pressure Region and is Often Associated with Elevated Ducts [From (Martin, 2007)]

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IV. SOUNDING DATA SETS AND MATLAB CODES

A. SOUNDING DATA SETS

The goal of this thesis is to quantify ducting climatology within Turkey and its surrounding areas. All the atmospheric upper air data sets were acquired from the Department of Atmospheric Science at the University of Wyoming. Five years worth of data were collected to calculate refractivity for ten different stations. Table 3 shows these stations and their locations.

Table 3. Stations and their Locations

Station Code	**Station Identifier**	**Location**
17351	--	Adana/Turkey
17130	--	Ankara/Turkey
17281	--	Diyarbakir/Turkey
17240	--	Isparta/Turkey
17062	--	Istanbul/Turkey
17220	--	Izmir/Turkey
16716	LGAT	Athens/Greece
15420	LRBS	Bucharest/Romania
16754	LGIR	Crete Island/Greece
37018	--	Tuapse/Russia

Figure 13. Geographic Locations of the Stations

The first few lines of sample data are shown in Figure 14. It is a detailed data set that includes all necessary parameters to calculate modified refractivity.

17062 Observations at 00Z 01 Jan 2005

PRES hPa	HGHT m	TEMP C	DWPT C	RELH %	MIXR g/kg	DRCT deg	SKNT knot	THTA K	THTE K	THTV K
1016.0	39	8.2	7.1	93	6.26	40	12	280.1	297.4	281.1
1015.0	47	8.2	7.1	93	6.26	80	7	280.1	297.4	281.2
1000.0	167	7.8	6.8	93	6.23	80	13	280.9	298.2	282.0

Figure 14. Sample Data

B. MATLAB CODES

The MATLAB codes used in this thesis for determining duct statistics are based on Stahlhut's (2006) routines that were written to calculate refractivity in the Arctic regions. The MATLAB routines were revised to input data from the University of Wyoming data sets. The MATLAB code is shown in the Appendix.

First, all soundings are read by MATLAB. After the modified refractivity is calculated for every height, the M gradient is calculated. According to the M gradients, the ducting conditions are determined for each profile. The lowest three ducts are examined if they exist. According to the duct bottom, surface duct existence is checked. Then key duct parameters are recorded for each station. Finally, an Excel sheet that includes the duct heights, duct thickness, duct gradient and other information related to the station is created. This cycle is done for every sounding for a year. All results are collected then saved as an Excel (.xls) file. This Excel file is loaded into MATLAB. To find statistics for one station the "statistics.m" program (see Appendix, Section D) is run. To find statistics for a month the ductformonth.m file is run before "statistics.m."

To calculate a modified refractivity at a given height, Equation 3.7 is used. Equation 4.1, gives the vapor pressure at a given height where the temperature, T, is in Celsius:

$$e(z) = 6.112e^{(17.67*T(z))/(243.12+T(z))} . \qquad (4.1)$$

The duct top and duct middle are the local minimum and local maximum of M, respectively, found by a switch in the sign of dM/dz. The duct bottom has the same value of M as at the duct top. It can be calculated by dropping a straight vertical line from duct top to the duct bottom. It can be found by applying simple geometry. Equation 4.2 gives the height of duct bottom (Stahlhut, 2006).

$$z^* = z_2 - \frac{M_2 - M^*}{M_2 - M_1}(z_2 - z_1) \quad . \qquad (4.2)$$

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V. RESULTS

A. DUCT FREQUENCY STATISTICS

The objective of this chapter is to evaluate the results gathered from MATLAB. In this study it is important to know and understand how ducting conditions can effect the performance of communication systems.

> A transmitter or receiver placed in a surface duct will experience significant signal enhancement, and long detection range. Omni-directional sources will experience cylindrical spreading loses, and narrow radar beams will view the duct as a waveguide. Existence of trapping layer is determined by a temperature increase and/or humidity decrease with height. (Cairns-McFeeters, 1992)

Table 4 shows frequency of occurrence of ducts during the five-year period from 2005-2009 for each station. Duct1 represents the lowest ducts that also include the surface-based ducts in Table 4. Duct2 is the first elevated ducts that are higher than the lowest ducts. Duct3 is the third highest ducts in M profiles.

The significant result is that the probability of occurrence of a duct is relatively high for all locations. If we compare day occurrence with night occurrence, it is clear that there is not much differences between them. For example, Istanbul's day occurrence frequency is 50.93 and its night occurrence frequency is 50.44. Although this conclusion is also true for other trapping layers, some stations have significant occurrence differences between night and day occurrences of surface ducts. The surface-based duct occurrence in Ankara, Istanbul, and Izmir is higher during day hours than night hours.

Table 4. Frequency of Ducts

Present occurrence of ducts during 24 hours	Duct1	Duct2	Duct3	Sf. Duct
17351 Adana	59.46	23.38	6.40	16.05
17131 Ankara	34.22	5.96	0.56	18.77
17281 Diyarbakir	37.53	6.18	0.56	21.92
17240 Isparta	38.15	8.29	0.84	22.00
17062 Istanbul	50.67	16.54	4.06	17.10
17220 Izmir	45.59	11.07	1.58	20.16
16716 Athens	64.69	18.94	3.27	44.20
15420 Bucharest	30.24	5.74	0.83	11.26
16754 Crete Island	65.59	23.81	5.57	29.45
37018 Tuapse	21.05	2.33	0.14	13.36

Present occurrence of ducts during day	Duct1	Duct2	Duct3	Sf. Duct
17351 Adana	51.56	19.34	4.00	23.10
17131 Ankara	43.53	9.95	0.85	32.00
17281 Diyarbakir	34.79	5.93	0.81	22.25
17240 Isparta	38.53	9.73	1.30	24.72
17062 Istanbul	50.93	17.45	4.69	25.92
17220 Izmir	52.85	14.94	2.34	33.35
16716 Athens	64.22	18.75	2.84	46.89
15420 Bucharest	28.50	5.13	0.61	12.27
16754 Crete Island	67.24	26.55	6.40	35.89
37018 Tuapse	22.89	2.53	0.07	15.24

Present occurrence of ducts during night	Duct1	Duct2	Duct3	Sf. Duct
17351 Adana	67.15	27.32	8.76	9.11
17131 Ankara	25.10	2.05	0.28	5.82
17281 Diyarbakir	40.18	6.41	0.33	21.60
17240 Isparta	37.80	6.90	0.40	19.41
17062 Istanbul	50.44	15.65	3.44	8.44
17220 Izmir	38.46	7.30	0.84	7.30
16716 Athens	65.23	19.19	3.61	42.30
15420 Bucharest	31.97	6.35	1.05	10.27
16754 Crete Island	63.91	20.87	4.75	22.66
37018 Tuapse	19.21	2.13	0.21	11.48

Table 5. Present Occurrence of First Duct by Month (Surface-based Duct is Included)

	Jan	Feb	Mar	Apr	May	Jun	Jly	Aug	Sep	Oct	Nov	Dec
17351 Adana	33.44	29.63	43.73	58.87	68.92	82.87	91.52	94.85	71.72	57.89	42.81	39.80
17131 Ankara	23.53	25.00	20.79	26.44	43.52	44.48	51.97	51.80	34.29	30.00	28.28	32.89
17281 Diyarbakir	18.72	27.19	27.05	37.45	56.77	53.95	62.81	55.14	47.12	24.57	23.89	21.90
17240 Isparta	20.20	16.86	23.31	30.98	45.85	57.39	66.54	67.93	48.78	37.46	25.17	21.43
17062 Istanbul	25.00	20.73	29.47	47.80	60.98	72.70	81.46	85.99	59.93	48.22	40.94	33.22
17220 Izmir	28.95	29.71	32.23	42.37	47.04	61.59	72.24	65.25	56.47	38.06	41.75	31.40
16716 Athens	46.49	44.08	56.43	69.51	72.28	83.12	83.06	83.77	75.83	63.30	57.29	53.21
15420 Bucharest	9.06	6.16	14.62	26.76	35.20	51.38	56.39	55.19	37.04	31.72	23.08	14.94
16754 Crete Island	44.68	41.87	54.31	62.45	69.62	88.70	84.85	85.09	75.90	66.67	66.67	56.79
37018 Tuapse	3.42	8.63	8.26	15.86	27.65	35.05	47.37	40.57	30.47	22.69	12.89	7.07

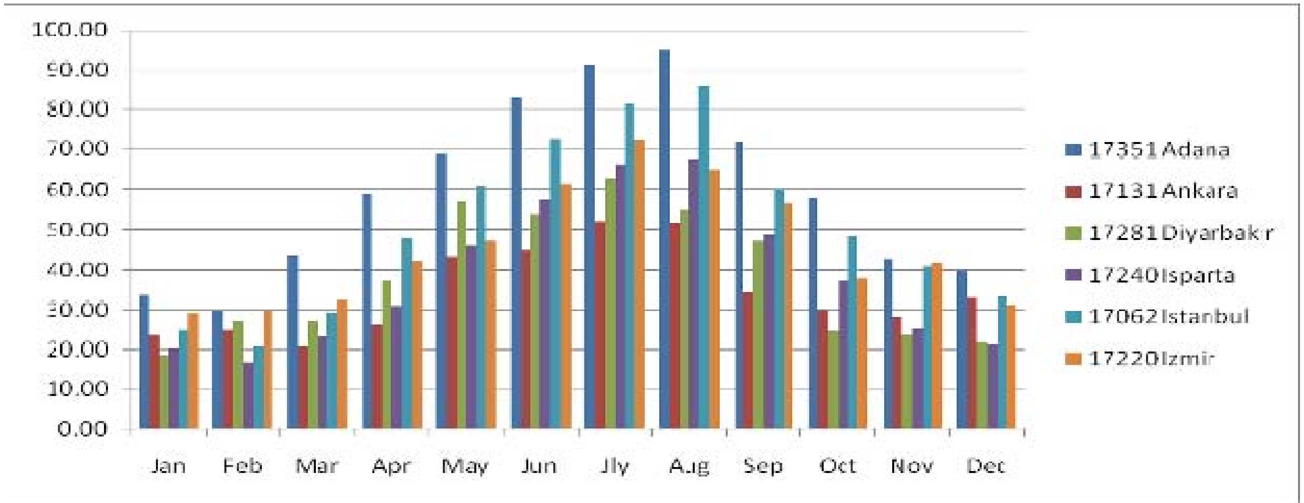

Figure 15. Frequencies of First Duct by Month (Turkey)

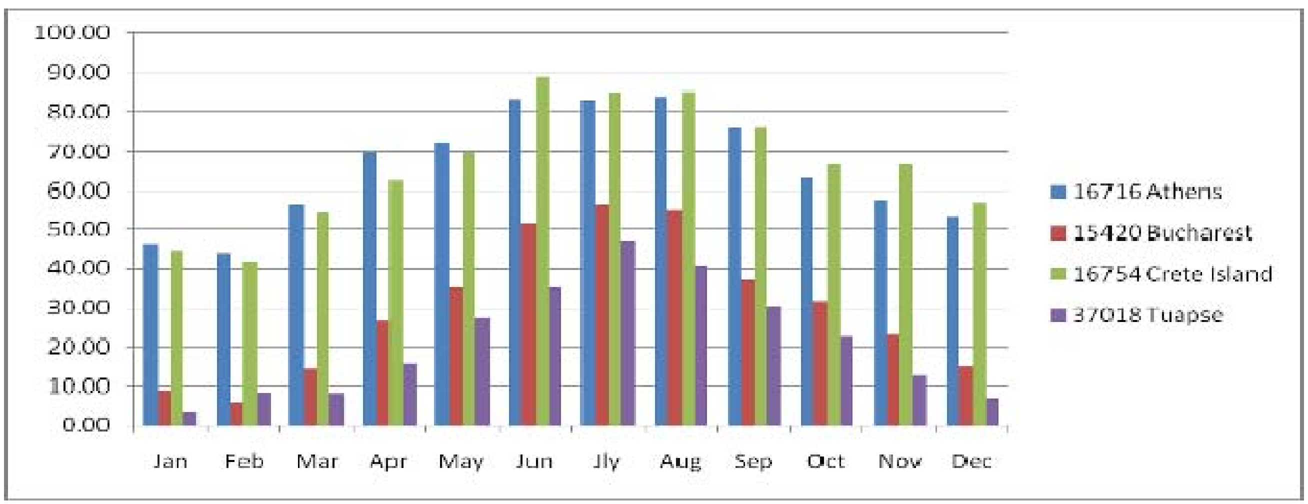

Figure 16. Frequencies of First Duct by Month (Athens, Bucharest, Crete Island, and Tuapse)

Table 5, Figure 15 and Figure 16 all show the distribution of first ducts (surface-based ducts are included) by month. It is clear that the ducts are most common during summer time. In Adana, there is greater than 90% probability of ducts occurring in July and August. The lowest occurrence of first ducts within Turkey was in February, at Isparta, with 17 percent of duct occurrence. This percentage rate of ducting conditions is significant, indicating that ducting may be a factor in all regions of Turkey during all times of the year. The highest occurrence of the stations outside of Turkey were Athens and Crete Island, where they have almost the same duct frequency trend because they are affected by the same climate conditions.

Comparing these results to AREPS (Advanced Refractive Effects Prediction System) climatology clearly shows that the percentage of duct occurrences for all stations is higher than AREPS's. Figure 17 and Figure 18 are the sample elevated duct frequency distributions by months for Ankara and Isparta from AREPS.

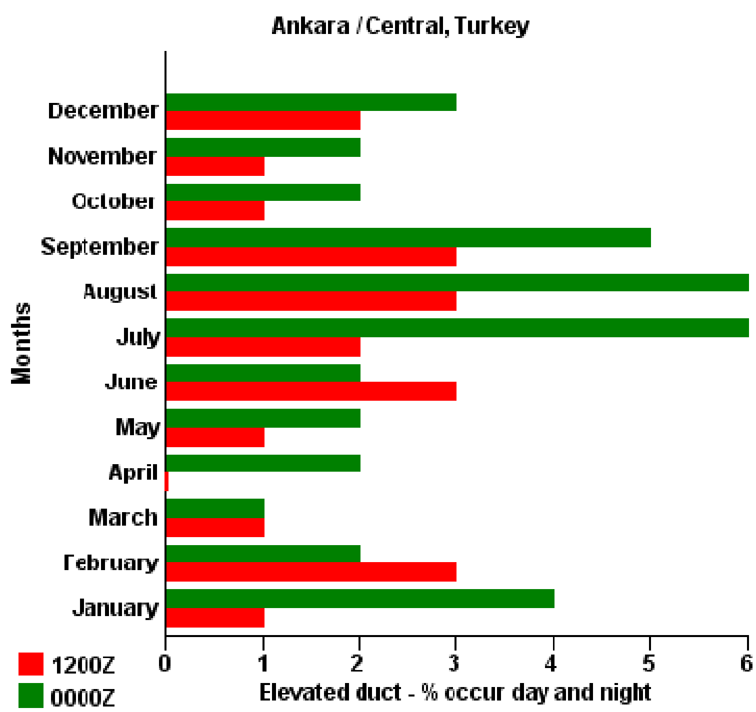

Figure 17. Elevated Duct Percent Occurance for Day and Night in Ankara

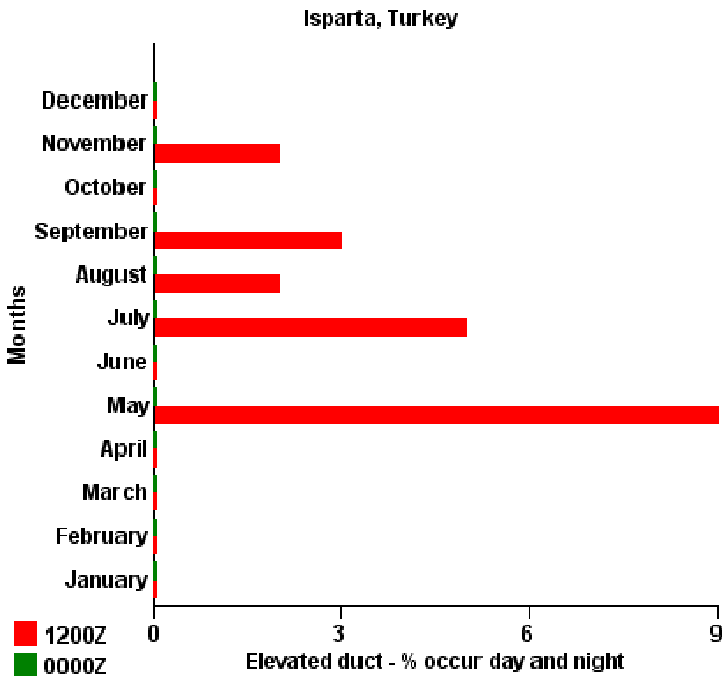

Figure 18. Elevated Duct Percent Occurance for Day and Night in Isparta

B. DUCT THICKNESS AND HEIGHT STATISTICS

The following formula, based on experimental results, is used to determine the minimum frequency that will be trapped by a duct of given thickness (d, in meters):

$$f_{\min} = \left(\frac{3.6x10^{11} Hz}{m^{\frac{-3}{2}}} \right) d^{\frac{-3}{2}} \tag{5.1}$$

Figure 19 represents the equations graphically, while Table 6 summarizes duct thickness ranges. Duct thickness statistics of the stations can be evaluated according to Table 6. It shows the common frequency ranges and the required duct depths to trap a signal in these frequency ranges (Davidson, 2003).

Table 6. Minimum Duct Thickness Required for Trapping Determined by Radar Frequency Band [From (Cairns-McFeeters, 1992)]

BAND	**Frequency Range**	**Duct Thickness (m)**
VHF	30 MHz – 300 MHz	122 – 610
UHF	300 MHz – 1 GHz	52 – 122
L	1 GHz – 2 GHz	32 – 52
S	2 GHz – 4 GHz	20 – 32
C	4 GHz – 8 GHz	12 – 20
X	8 GHz – 12 GHz	9 – 12
K	12 GHz - 40GHz	4 – 9

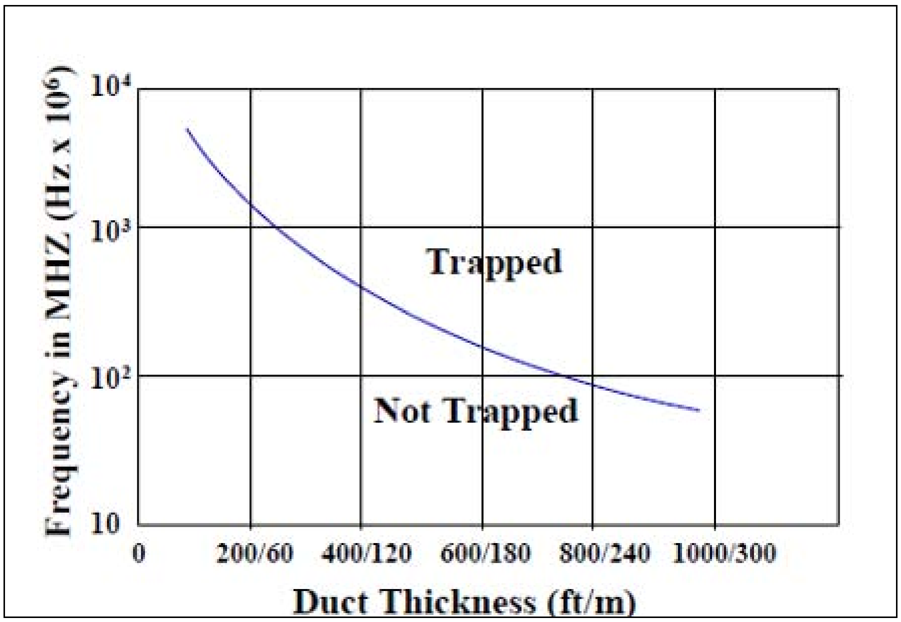

Figure 19. Minimum Trapping Frequency [From (Davidson, 2003)]

Table 7 displays the height statistics of ducts and Table 8 shows the thickness of the first three and surface ducts. Heights are above sea level. Surface ducts are very shallow for all stations. Note from Table 6 that in many cases, only the highest frequency transmissions will be trapped. In addition, topographic features such as hills are usually higher than the duct, which also would prevent the normally extended ranges associated with ducting situations. Although over water and other flat locations microwaves may have extended ranges due to the ducts, in most cases these shallow surface ducts are not operationally significant. We can compare duct thicknesses of our locations with Table 6 above. There is a reverse relationship between frequency and duct thickness. As frequency increases, the required duct thickness to send a signal decreases. The mean height above sea level of first ducts in Turkey is around 850±100 meters for all stations. Bucharest has the highest mean thickness of surface ducts at only 74.5 meters. According to Table 6, this would trap radiation in the UHF and higher frequency band ranges. If we examine the other layers, Adana has the highest mean thickness at 199.9 meters.

Table 7. Duct Height Statistics

ADANA (ABOVE SEA LEVEL 25m)	Duct1	Duct2	Duct3	Sf. Duct
Mean Height (m)	856.2	1863.6	2543.6	59.1
Lower Quartile (m)	86.0	1087.0	1550.5	36.0
Median (m)	565.0	1535.5	2222.5	45.0
Higher Quartile (m)	1346.0	2504.5	3552.5	64.0
Std. Dev. (m)	970.1	1076.6	1239.3	34.7
ANKARA (ABOVE SEA LEVEL 891m)	Duct1	Duct2	Duct3	Sf. Duct
Mean Height (m)	1824.9	3169.3	3266.7	907.4
Lower Quartile (m)	901.0	2651.0	2973.0	900.0
Median (m)	920.0	3186.0	3381.0	901.0
Higher Quartile (m)	2847.0	3730.0	3670.0	910.0
Std. Dev. (m)	1201.3	851.5	679.8	12.8
DIYARBAKIR (ABOVE SEA LEVEL 675m)	Duct1	Duct2	Duct3	Sf. Duct
Mean Height (m)	1417.2	3267.6	4213.9	695.8
Lower Quartile (m)	685.0	2362.0	3589.0	684.0
Median (m)	706.5	3509.5	3971.0	691.0
Higher Quartile (m)	1510.0	4218.0	4987.5	700.0
Std. Dev. (m)	1293.9	1413.4	872.4	18.4
ISPARTA (ABOVE SEA LEVEL 997m)	Duct1	Duct2	Duct3	Sf. Duct
Mean Height (m)	1759.2	3461.2	3502.7	1022.7
Lower Quartile (m)	1016.0	2960.0	2910.5	1007.0
Median (m)	1036.0	3507.0	3285.0	1016.0
Higher Quartile (m)	2706.0	3949.0	4030.0	1027.0
Std. Dev. (m)	1122.6	886.8	753.7	19.9
ISTANBUL (ABOVE SEA LEVEL 39m)	Duct1	Duct2	Duct3	Sf. Duct
Mean Height (m)	787.9	1668.0	2447.5	63.5
Lower Quartile (m)	65.0	941.5	1563.0	48.0
Median (m)	419.0	1485.0	2373.0	56.0
Higher Quartile (m)	1260.0	2264.0	3257.5	68.0
Std. Dev. (m)	927.7	1003.4	1094.7	24.4
IZMIR (ABOVE SEA LEVEL 29m)	Duct1	Duct2	Duct3	Sf. Duct
Mean Height (m)	952.9	2062.5	2528.6	51.0
Lower Quartile (m)	49.0	1292.0	1531.0	38.0
Median (m)	174.0	1971.0	2470.0	46.0
Higher Quartile (m)	1718.0	2718.0	3404.5	57.0
Std. Dev. (m)	1193.0	1056.9	1217.1	15.5

ATHENS (ABOVE SEA LEVEL 15m)	Duct1	Duct2	Duct3	Sf. Duct
Mean Height (m)	505.1	1864.6	2747.9	53.8
Lower Quartile (m)	39.0	743.0	1928.5	32.0
Median (m)	59.5	1849.0	2773.0	47.0
Higher Quartile (m)	186.0	2774.0	3390.0	65.0
Std. Dev. (m)	979.8	1261.9	1300.7	31.3
BUCHAREST (ABOVE SEA LEVEL 91m)	Duct1	Duct2	Duct3	Sf. Duct
Mean Height (m)	953.0	2540.9	3443.2	157.6
Lower Quartile (m)	154.0	1788.0	2858.0	139.0
Median (m)	253.5	2474.0	3407.0	150.0
Higher Quartile (m)	1585.0	3161.0	3953.0	167.0
Std. Dev. (m)	1153.9	1155.8	899.7	33.2
CRETE ISLAND (ABOVE SEA LEVEL 39m)	Duct1	Duct2	Duct3	Sf. Duct
Mean Height (m)	761.5	1515.4	2428.7	80.1
Lower Quartile (m)	73.0	488.0	1270.0	56.0
Median (m)	189.5	1193.0	2126.0	72.0
Higher Quartile (m)	1238.0	2142.5	3311.5	95.0
Std. Dev. (m)	1021.8	1251.7	1513.9	39.0
TUAPSE (ABOVE SEA LEVEL 95m)	Duct1	Duct2	Duct3	Sf. Duct
Mean Height (m)	589.2	1652.5	1539.5	133.7
Lower Quartile (m)	116.0	788.0	1034.0	109.5
Median (m)	139.0	1566.0	1575.0	121.0
Higher Quartile (m)	782.0	2207.5	2045.0	136.0
Std. Dev. (m)	1087.9	990.8	608.1	50.5

Table 8. Duct Thickness Statistics

ADANA (ABOVE SEA LEVEL 25m)	Duct1	Duct2	Duct3	Sf. Duct
Mean Thickness (m)	147.5	199.9	156.6	58.2
Lower Quartile (m)	35.0	91.0	78.6	14.0
Median (m)	104.3	155.5	119.3	26.0
Higher Quartile (m)	212.2	277.6	184.9	139.0
Std. Dev. (m)	140.4	144.8	121.2	74.9
ANKARA (ABOVE SEA LEVEL 891m)	Duct1	Duct2	Duct3	Sf. Duct
Mean Thickness (m)	52.2	95.1	69.7	16.4
Lower Quartile (m)	10.0	59.0	41.1	9.0
Median (m)	28.0	87.9	62.2	10.0
Higher Quartile (m)	87.3	124.7	88.4	58.0
Std. Dev. (m)	52.5	49.7	34.3	12.8
DIYARBAKIR (ABOVE SEA LEVEL 675m)	Duct1	Duct2	Duct3	Sf. Duct
Mean Thickness (m)	45.2	81.8	79.3	22.6
Lower Quartile (m)	10.0	46.3	47.8	9.0
Median (m)	26.0	75.0	80.6	17.0
Higher Quartile (m)	68.8	113.9	112.8	52.1
Std. Dev. (m)	45.0	48.6	36.2	22.0
ISPARTA (ABOVE SEA LEVEL 997m)	Duct1	Duct2	Duct3	Sf. Duct
Mean Thickness (m)	51.8	90.3	66.3	28.4
Lower Quartile (m)	19.0	60.7	39.4	10.0
Median (m)	36.2	83.4	50.6	19.0
Higher Quartile (m)	75.9	116.5	92.5	57.0
Std. Dev. (m)	45.7	41.5	40.3	24.5
ISTANBUL (ABOVE SEA LEVEL 39m)	Duct1	Duct2	Duct3	Sf. Duct
Mean Thickness (m)	116.4	153.7	122.4	41.8
Lower Quartile (m)	24.0	85.9	60.3	9.0
Median (m)	84.0	133.5	104.5	18.0
Higher Quartile (m)	170.0	191.1	166.8	112.6
Std. Dev. (m)	113.3	100.2	79.7	69.5
IZMIR (ABOVE SEA LEVEL 29m)	Duct1	Duct2	Duct3	Sf. Duct
Mean Thickness (m)	70.4	121.7	118.0	26.6
Lower Quartile (m)	17.0	76.9	53.9	9.0
Median (m)	44.0	112.6	90.7	17.0
Higher Quartile (m)	105.6	158.5	160.7	71.9
Std. Dev. (m)	67.3	66.6	80.9	31.9

ATHENS (ABOVE SEA LEVEL 15m)	Duct1	Duct2	Duct3	Sf. Duct
Mean Thickness (m)	59.3	116.9	99.3	42.0
Lower Quartile (m)	24.0	69.4	63.0	17.0
Median (m)	40.0	106.1	86.9	32.0
Higher Quartile (m)	81.6	154.1	123.6	68.9
Std. Dev. (m)	54.5	67.8	53.8	37.4
BUCHAREST (ABOVE SEA LEVEL 91m)	Duct1	Duct2	Duct3	Sf. Duct
Mean Thickness (m)	93.8	126.5	87.7	74.5
Lower Quartile (m)	53.0	79.6	45.6	47.2
Median (m)	73.8	111.1	77.7	61.0
Higher Quartile (m)	121.0	167.0	131.0	109.0
Std. Dev. (m)	60.6	67.0	52.7	43.5
CRETE ISLAND (ABOVE SEA LEVEL 675m)	Duct1	Duct2	Duct3	Sf. Duct
Mean Thickness (m)	96.5	138.5	107.0	51.8
Lower Quartile (m)	28.6	71.0	50.3	19.0
Median (m)	65.0	124.8	93.7	34.0
Higher Quartile (m)	139.7	188.3	139.5	106.0
Std. Dev. (m)	90.2	87.6	82.6	59.0
TUAPSE (ABOVE SEA LEVEL 997m)	Duct1	Duct2	Duct3	Sf. Duct
Mean Thickness (m)	76.2	135.8	110.9	39.8
Lower Quartile (m)	19.0	84.0	55.8	15.0
Median (m)	38.0	106.5	105.9	26.0
Higher Quartile (m)	96.9	156.2	165.9	68.0
Std. Dev. (m)	94.0	86.8	75.6	51.7

C. CORRELATIONS WITH METEOROLOGICAL PARAMETERS

To provide guidance on what factors may be related to duct occurrence, surface pressure, wind speed, and wind direction were plotted against duct height to determine if there are any correlations that could be used to make more accurate predictions of duct occurrence. Although these meteorological parameters are not directly related to ducting (which depends primarily on vertical variations in humidity), the hypothesis is that these parameters may affect the humidity profiles which in turn would be related to ducting probabilities. For example, wind speed may affect atmospheric mixing of water vapor (humidity) which results in changes in ducting statistics. Wind direction could be correlated with moisture advection (horizontal movement), especially in coastal regions where it would be expected than air coming from over the water would have different humidity, and hence ducting characteristics. Higher surface pressure is associated with sinking air motion, which is often associated with the formation of an elevated temperature inversion (increase in temperature with height), and a strong decrease in humidity going up through the inversion. It is well known that in most locations ducting is correlated with high pressure.

Scatter plots of these atmospheric parameters and duct height were created for all stations. Only those stations with significant correlations are displayed in this section. The most significant conclusion for wind speed and wind direction is that they do not appear to have a significant effect on duct heights for most stations, though some exceptions are shown below. It can also be seen that, from plots for some stations, there is a positive relation between duct height and surface pressure. This is somewhat unexpected because the sinking air associated with high pressure was expected to push the duct heights lower.

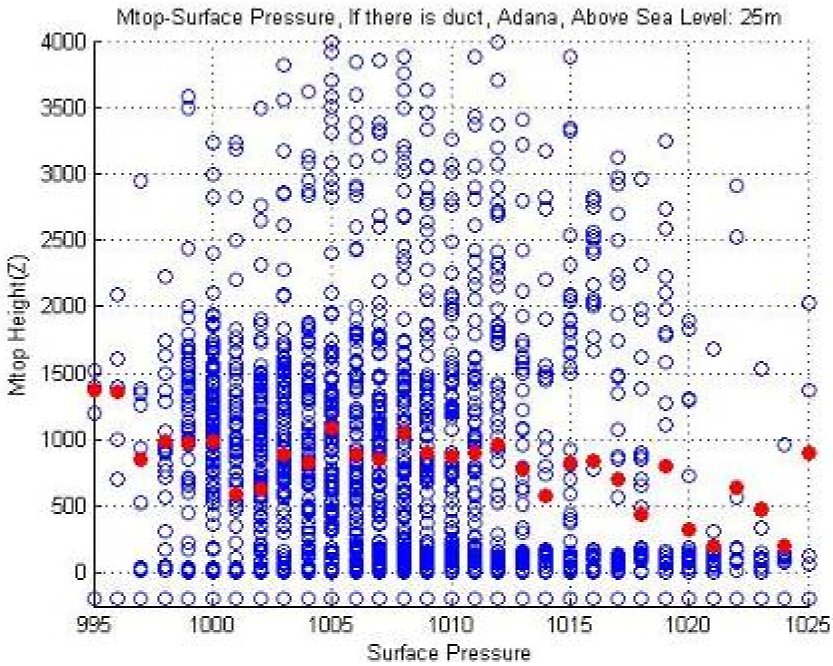

Figure 20. Height (m) and Surface Pressure (milibar) Correlation for Adana (if a Duct Presents)

Figure 20 shows that a higher pressure was associated with lower ducts at Adana. Isparta (Figure 22) also has the same pattern. If we examine Figure 21, which is for surface ducts only, it is clearly determined that if the surface pressure increases, the duct height also increases. This may be because the shallower ducts are associated with shallow temperature inversions caused by radiational cooling (which does not require high pressure) while the deeper ducts may be more associated with the elevated inversions caused by sinking air.

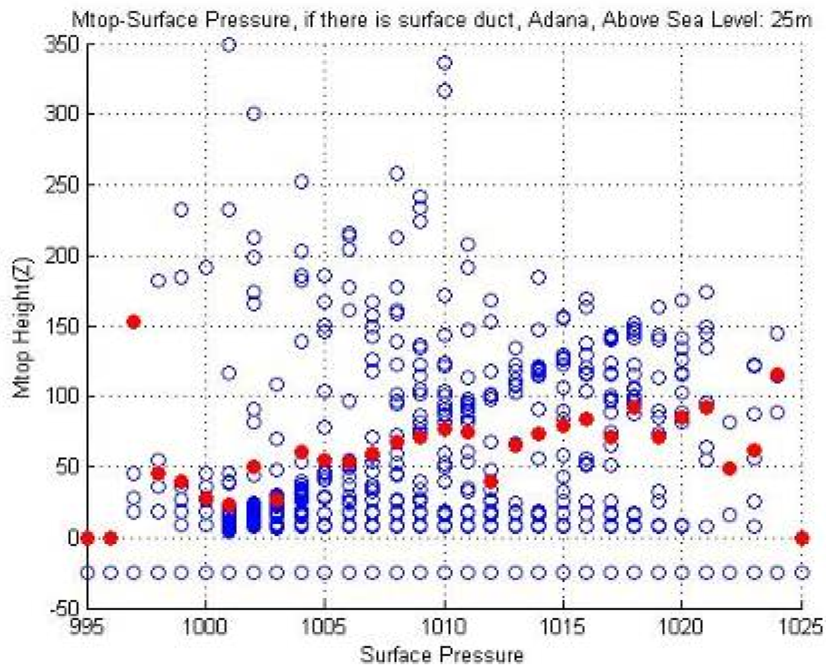

Figure 21. Height (m) and Surface Pressure (milibar) Correlation for Adana (if only a Surface Duct Presents)

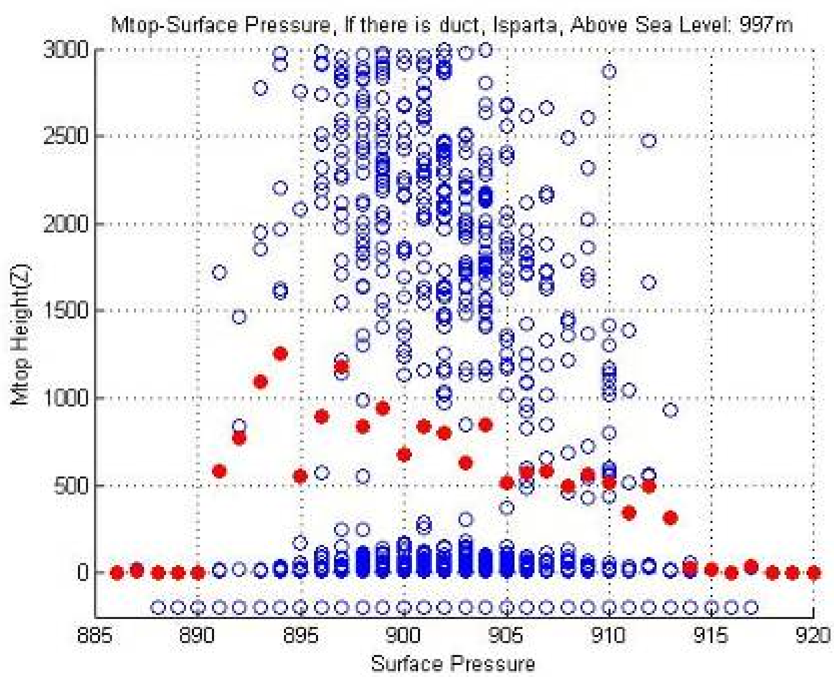

Figure 22. Height (m) and Surface Pressure (milibar) Correlation for Isparta (if a Duct Presents)

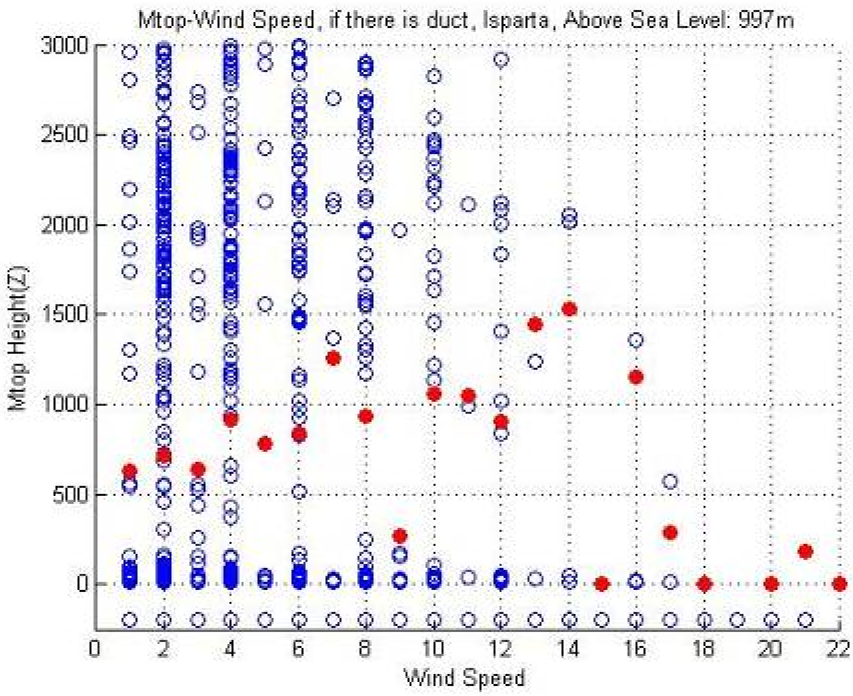

Figure 23. Height (m) and Wind Speed (knot) Correlation for Isparta (if a Duct Presents)

For Isparta, there is a positive relationship between wind speed and duct height if there is any type of duct (Figure 23).

Figure 24 and Figure 28 are other examples of a positive relationship between surface pressure and duct height, if any duct is present or if only a surface duct exists. Figure 26 shows that if the wind direction switches form east through north in Istanbul, it is possible to see more numbers of ducts. In Bucharest, if the wind speed increases the duct height also increases (Figure 27).

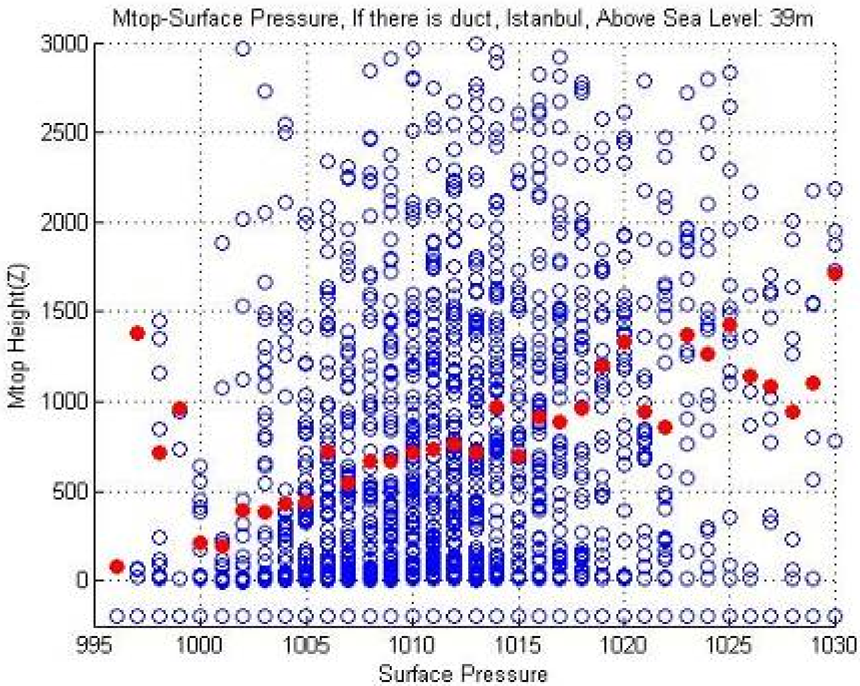

Figure 24. Height (m) and Surface Pressure (milibar) Correlation for Istanbul (if a Duct Presents)

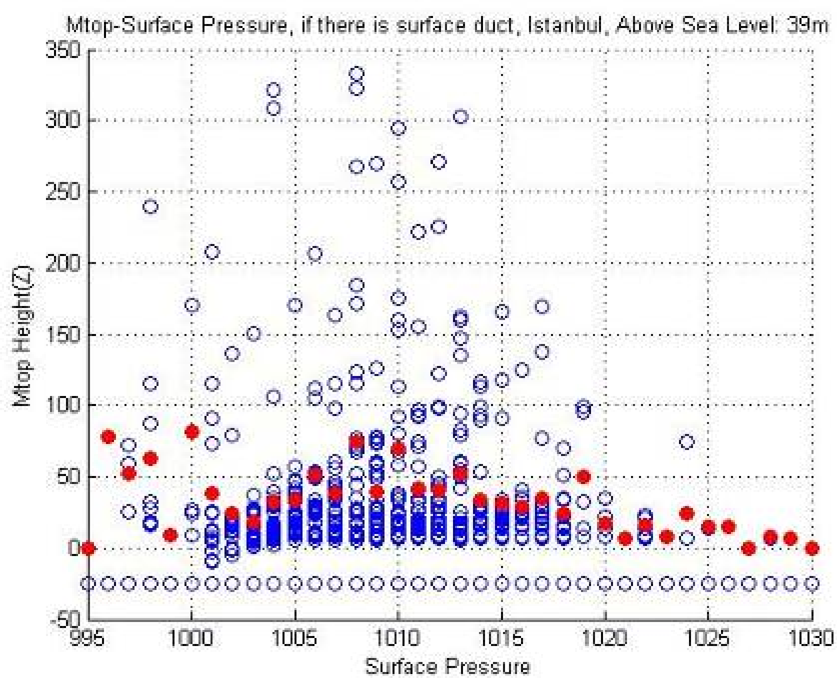

Figure 25. Height (m) and Surface Pressure (milibar) Correlation for Istanbul (if Only a Surface Duct Presents)

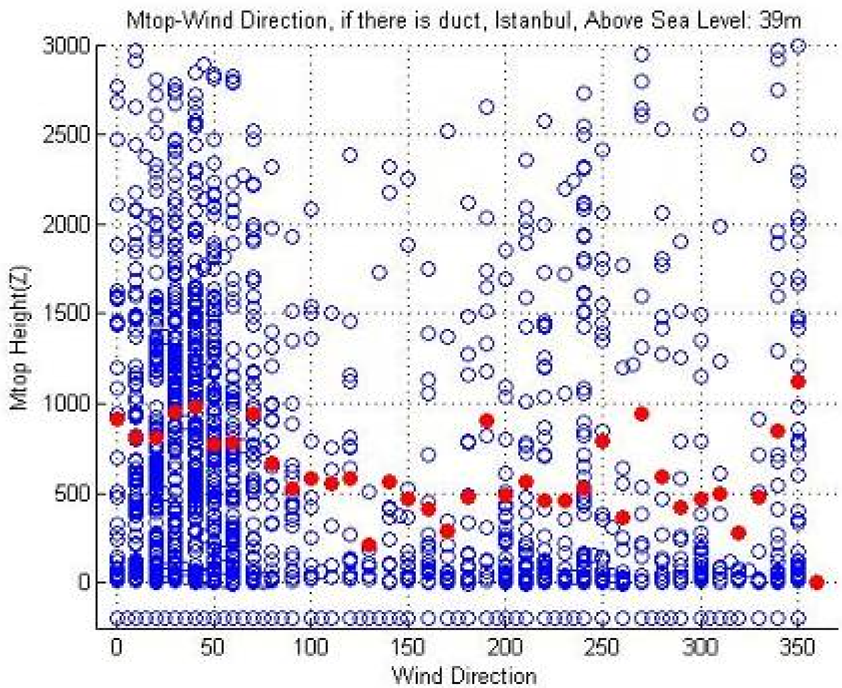

Figure 26. Height (m) and Wind Direction (degree) Correlation for Istanbul (if a Duct Presents)

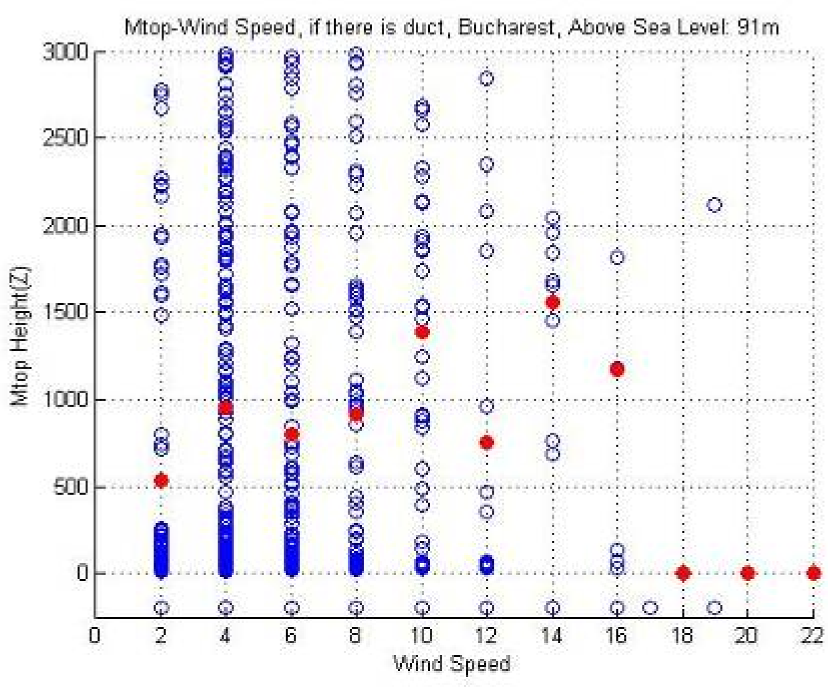

Figure 27. Height (m) and Wind Speed (knot) Correlation for Bucharest (if a Duct Presents)

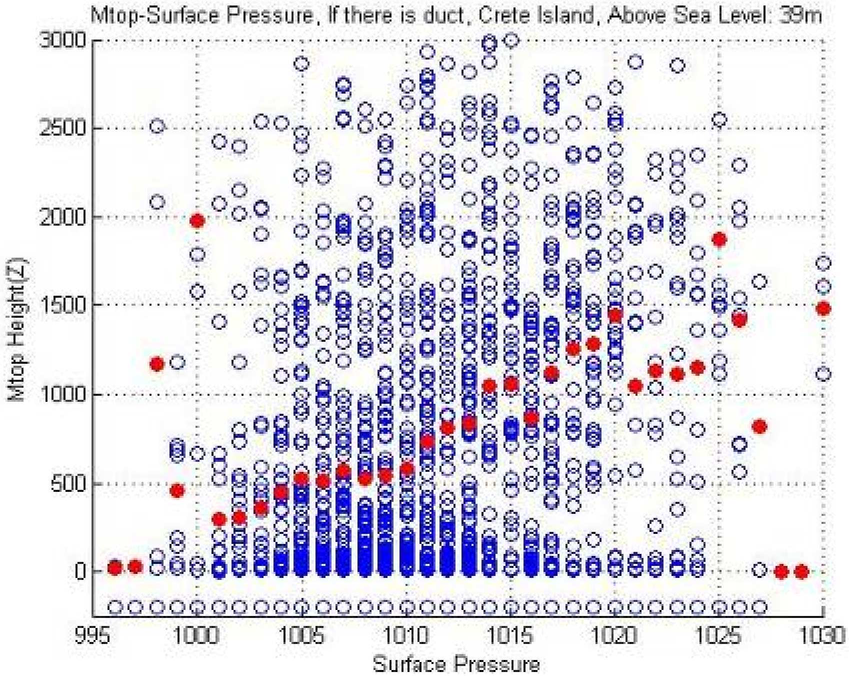

Figure 28. Height (m) and Surface Pressure (milibar) Correlation for Crete Island (if a Duct Presents)

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VI. CONCLUSION

The purpose of this thesis was to characterize ducting climatology within Turkey and its surrounding areas. Almost 36,500 lines of data, representing different elevations, stations and times, were processed. Refractivity profile statistics for each station were calculated. The general trend of duct occurrences and the relationship between duct height and other parameters were quantified.

According to the results, the probability of duct occurrence is higher in summer months. Wind speed and wind direction do not have much effect on ducting for most stations. There is a positive relationship between surface pressure and duct height at some stations. This condition was not an expected situation. A likely explanation is that very shallow ducts, associated with surface radiational cooling or other local effects, are often present during both high and low pressure situations, but the higher ducts are associated more with higher pressure. Therefore, when considering all ducts, the average height is higher for high-pressure situations. Although there are many ducts, they are not so important for VHF and lower frequencies because their thickness is not enough to send a signal in VHF and lower frequency ranges. These ducts can be important for systems that use a microwave frequency range (UHF and EHS). For example, radar uses microwave radiation to detect the range of remote objects.

The plots, tables, and figures provided in this thesis can be a guide for Electronic Warfare Systems and radio operators and their commanders. By using knowledge of the environment and its affect on radio transmissions, we can gain an advantage over adversaries who do not consider this information in planning and carrying out military operations. It can also be helpful for civilian use of radio transmissions. The most significant threat is losing communication links.

Knowing the technical information about an EW system and having the ability to predict atmospheric conditions can greatly enhance the communication capabilities of Turkey and its allies.

APPENDIX

A. MATLAB PROGRAM TO READ DATA

```
function loadsnd(filename)
fid_in=fopen(filename,'r');
if fid_in > 0
    sprintf('Sounding file opened: %s',filename)
end
tic
% counter for all data
bigcounter = 0;
%This loop for all year
while 1
    % Skip first five rows header
    for ihead = 1:5;
        line = fgetl(fid_in);
    end
    %
    %initialize a line counter
    iline=0;
    %
    %This loop reads each line
    while 1
        %Read each line as a character string
        line=fgetl(fid_in) ;
        %This loop finds missing value for dwpt
        while line (22:28) == '       '
            line=fgetl(fid_in);
        end
        %This is statement for reading headers
        if line (1:7) == 'Station'
            line=fgetl(fid_in);
            line=fgetl(fid_in);
            station = str2num(line(46:50));
            line=fgetl(fid_in);
            date=str2num(line(46:51));
            time=str2num(line(53:56));
            line=fgetl(fid_in);
            %This loop skip other lines
            while ~isempty(line) %line(44) == ':'
                line=fgetl(fid_in);
                %Check for the effective "end-of-file"
                if line == -1
                    break
                end
            end
        end
        %Check for the end of one data set
        if isempty(line)
            break
        end
```

```
    %Check for the effective "end-of-file"
    if line == -1
        break
    end
    %Increment line counter.  This is the index for each data array
    iline = iline+1;
    %Reads data from file
    pres(iline) = str2num(line(1:7));
    disp(pres(iline));
    hght(iline) = str2num(line(8:14));
    tmpc(iline) = str2num(line(15:21));
    dwpc(iline) = str2num(line(22:28));
    relh(iline) = str2num(line(29:35));
    mixr(iline) = str2num(line(36:42));

    if line(48:56) ==='         '
        drct(iline) = NaN;
        sknt(iline) = NaN;
    else
        drct(iline) = str2num(line(47:49));
        sknt(iline) = str2num(line(54:56));
    end

end     % This is the end of the WHILE Loop


% Calculate theta & q
[thta,q] = theta_q(pres,tmpc,relh);
% Calculate M and N
[M,N] = m_n_profile(pres,tmpc,relh,hght);
% Calculates the Modified Refractivity gradient
Mgrad=NaN;
for n=1:iline-1 ;
    Mgrad(n,1)=(M(n+1) - M(n)) /(hght(n+1) - hght(n));
end
bigcounter = bigcounter + 1;

% This portion finds the first three ducts, if
% they exist
ducttop=[0 0 0];
ductmiddle=[0 0 0];
ductbottom=[0 0 0];
Ttop=NaN;
Dewtop=NaN;
Presstop=NaN;
Mtop=NaN;
Tmid=NaN;
Dewmid=NaN;
Pressmid=NaN;
Mmid=NaN;
Mtop2=NaN;
Mmid2=NaN;
Mtop3=NaN;
Mmid3=NaN;
```

```
    % Find tops and mids of ducts....
    topcounter=0;
    midcounter=0;
    topindex=[0 0 0];
    midindex=[0 0 0];
    for m=2:length(Mgrad)
        if ((Mgrad(m-1) < 0) && (Mgrad (m) > 0))
            topcounter=topcounter+1;
            topindex(topcounter)=m;
        end
        if ((Mgrad(m-1) > 0) && (Mgrad (m) < 0))
            midcounter=midcounter+1;
            midindex(midcounter)=m;
        end
    end
    % Align these depending on case.....
    % If the gradient starts negative from the surface,
    % the subsequent indexing is different that for the
    % case if the gradient starts positive from the surface.
    if (Mgrad(1) <  0)
        if (topindex(1) > 0)
            ducttop(1)=hght(topindex(1));
            ductmiddle(1)=hght(1);
            ductbottom(1)=hght(1);
        end
        if (topindex(2) > 0) && (midindex(1) > 0)
            ducttop(2)=hght(topindex(2));
            ductmiddle(2)=hght(midindex(1));
            if M(midindex(1)-1) < M(topindex(2))
                ductbottom(2)=ductmiddle(2) - ...
                    (M(midindex(1))-M(topindex(2)))/...
                    (M(midindex(1))-M(midindex(1)-1))*...
                    (hght(midindex(1)) - hght(midindex(1)-1));
            elseif M(midindex(1)-1) > M(topindex(2))&& M(midindex(1)-
2)>M(midindex(1)-1)
                ductbottom(2)=hght(midindex(1)-1);
            elseif M(midindex(1)-2) > M(topindex(2))&& M(midindex(1)-
3)>M(midindex(1)-2)
                ductbottom(2)=hght(midindex(1)-2);
            elseif M(midindex(1)-1) > M(topindex(2))
                counterindex = 1;
                while M(midindex(1)-counterindex)>M(topindex(2))&&...
                        (midindex(1)-counterindex)~=1
                    counterindex = counterindex+1;
                end
                ductbottom(2)=hght(midindex(1)-counterindex+2) - ...
                    (M(midindex(1)-counterindex+2)-M(topindex(2)))/...
                    (M(midindex(1)-counterindex+2)-M(midindex(1)-
counterindex))*...
                    (hght(midindex(1)-counterindex+2) -
hght(midindex(1)-counterindex));
            end
            Mtop2=M(topindex(2));
            Mmid2=M(midindex(1));
        end
```

```
        if (topindex(3) > 0) && (midindex(2) > 0)
            ducttop(3)=hght(topindex(3));
            ductmiddle(3)=hght(midindex(2));
            if M(midindex(2)-1) < M(topindex(3))
                ductbottom(3)=ductmiddle(3) - ...
                    (M(midindex(2))-M(topindex(3)))/...
                    (M(midindex(2))-M(midindex(2)-1))*...
                    (hght(midindex(2)) - hght(midindex(2)-1));
            elseif M(midindex(2)-1) > M(topindex(3))
                counterindex = 1;
                while M(midindex(2)-counterindex)>M(topindex(3))
                    counterindex = counterindex+1;
                end
                ductbottom(3)=hght(midindex(2)-counterindex+2) - ...
                    (M(midindex(2)-counterindex+2)-M(topindex(3)))/...
                    (M(midindex(2)-counterindex+2)-M(midindex(2)-
counterindex))*...
                    (hght(midindex(2)-counterindex+2) -
hght(midindex(2)-counterindex));
            end
            Mtop3=M(topindex(3));
            Mmid3=M(midindex(2));
        end
        Ttop=tmpc(topindex(1));
        Dewtop=dwpc(topindex(1));
        Presstop=pres(topindex(1));
        Mtop=M(topindex(1));
        Tmid=tmpc(1);
        Dewmid=dwpc(1);
        Pressmid=pres(1);
        Mmid=M(1);
    end

    % These are for the cases when the gradient starts
    % positive, and there is a duct present somewhere in
    % the profile
    if (Mgrad(1) > 0) & (topindex(1) > 0)
        if (topindex(1) > 0) & (midindex(1) > 0) & ...
                (M(topindex(1)) < M(1))
            ducttop(1)=hght(topindex(1));
            ductmiddle(1)=hght(midindex(1));
            ductbottom(1)=hght(1);
        end

        if (topindex(1) > 0) & (midindex(1) > 0) & ...
                (M(topindex(1)) > M(1))
            ducttop(1)=hght(topindex(1));
            ductmiddle(1)=hght(midindex(1));
            if M(midindex(1)-1)<M(topindex(1))
                ductbottom(1)=ductmiddle(1) - ...
                    (M(midindex(1))-M(topindex(1)))/...
                    (M(midindex(1))-M(midindex(1)-1))*...
                    (hght(midindex(1)) - hght(midindex(1)-1));
            elseif M(midindex(1)-1)>M(topindex(1))
                counterindex = 1;
```

```
                while M(midindex(1)-counterindex)>M(topindex(1))
                    counterindex = counterindex+1;
                end
                ductbottom(1)=hght(midindex(1)-counterindex+2) - ...
                    (M(midindex(1)-counterindex+2)-M(topindex(1)))/...
                    (M(midindex(1)-counterindex+2)-M(midindex(1)-
counterindex))*...
                    ((hght(midindex(1)-counterindex+2)) -
hght(midindex(1)-counterindex));
            end
        end

        if (topindex(2) > 0) & (midindex(2) > 0)
            ducttop(2)=hght(topindex(2));
            ductmiddle(2)=hght(midindex(2));
            ductbottom(2)=ductmiddle(2) - ...
                (M(midindex(2))-M(topindex(2)))/...
                (M(midindex(2))-M(midindex(2)-1))*...
                (hght(midindex(2)) - hght(midindex(2)-1));
            if M(midindex(2)-1)<M(topindex(2))
                ductbottom(2)=ductmiddle(2) - ...
                    (M(midindex(2))-M(topindex(2)))/...
                    (M(midindex(2))-M(midindex(2)-1))*...
                    (hght(midindex(2)) - hght(midindex(2)-1));
            elseif M(midindex(2)-1)>M(topindex(2))
                counterindex = 1;
                while M(midindex(2)-counterindex)>M(topindex(2))&&...
                        (midindex(2)-counterindex)~=1
                    counterindex = counterindex+1;
                end
                ductbottom(2)=hght(midindex(2)-counterindex+2) - ...
                    (M(midindex(2)-counterindex+2)-M(topindex(2)))/...
                    (M(midindex(2)-counterindex+2)-M(midindex(2)-
counterindex))*...
                    ((hght(midindex(2)-counterindex+2)) -
hght(midindex(2)-counterindex));
            end
            Mtop2=M(topindex(2));
            Mmid2=M(midindex(2));
        end

        if (topindex(3) > 0) & (midindex(3) > 0)
            ducttop(3)=hght(topindex(3));
            ductmiddle(3)=hght(midindex(3));
            ductbottom(3)=ductmiddle(3) - ...
                (M(midindex(3))-M(topindex(3)))/...
                (M(midindex(3))-M(midindex(3)-1))*...
                (hght(midindex(3)) - hght(midindex(3)-1));
            if M(midindex(3)-1)<M(topindex(3))
                ductbottom(3)=ductmiddle(3) - ...
                    (M(midindex(3))-M(topindex(3)))/...
                    (M(midindex(3))-M(midindex(3)-1))*...
                    (hght(midindex(3)) - hght(midindex(3)-1));
            elseif M(midindex(3)-1)>M(topindex(3))
                counterindex = 1;
```

```
                while M(midindex(3)-counterindex)>M(topindex(3))
                    counterindex = counterindex+1;
                end
                ductbottom(3)=hght(midindex(3)-counterindex+2) - ...
                    (M(midindex(3)-counterindex+2)-M(topindex(3)))/...
                    (M(midindex(3)-counterindex+2)-M(midindex(3)-
counterindex))*...
                    ((hght(midindex(3)-counterindex+2))-
hght(midindex(3)-counterindex));
            end
            Mtop3=M(topindex(3));
            Mmid3=M(midindex(3));
        end

        Ttop=tmpc(topindex(1));
        Dewtop=dwpc(topindex(1));
        Presstop=pres(topindex(1));
        Mtop=M(topindex(1));
        Tmid=tmpc(midindex(1));
        Dewmid=dwpc(midindex(1));
        Pressmid=pres(midindex(1));
        Mmid=M(midindex(1));

        if topindex(2)~=0 && midindex(2)~=0
            Mtop2=M(topindex(2));
            Mmid2=M(midindex(2));
        else
            Mtop2=NaN;
            Mmid2=NaN;
        end
        if topindex(3)~=0 && midindex(3)~=0
            Mtop3=M(topindex(3));
            Mmid3=M(midindex(3));
        else
            Mtop3=NaN;
            Mmid3=NaN;
        end
    end
    if ductbottom(1) < 0
        ductbottom(1)=ductmiddle(1)-[ducttop(1)-ductmiddle(1)];
    end
    if ductbottom(2) < 0
        ductbottom(2)=ductmiddle(2)-[ducttop(2)-ductmiddle(2)];
    end
    if ductbottom(1) < 0
        ductbottom(1) =0;
    end
    if ductbottom(2) < 0
        ductbottom(2) =0;
    end
```

```
% This will assign a true/false value if
% the lowest duct is "attached" to or
% "elevated" from the surface
if [ducttop(1) > 0] & [ductbottom(1) > hght(1)]
    sfcduct=0;
elseif ([ducttop(1) > 0] & [ductbottom(1) == hght(1)]) |...
        ([ducttop(1) > 0] & [ductbottom(1) == 0])
    sfcduct=1;
else
    sfcduct=NaN;
end
% Assigns needed data to the Plotdata matrix
Plotdata(bigcounter,1)=station;
Plotdata(bigcounter,2)=date;
Plotdata(bigcounter,3)=time;
Plotdata(bigcounter,4)=Ttop;
Plotdata(bigcounter,5)=Dewtop;
Plotdata(bigcounter,6)=ducttop(1);
Plotdata(bigcounter,7)=ductmiddle(1);
Plotdata(bigcounter,8)=ductbottom(1);
Plotdata(bigcounter,9)=ducttop(2);
Plotdata(bigcounter,10)=ductmiddle(2);
Plotdata(bigcounter,11)=ductbottom(2);
Plotdata(bigcounter,12)=ducttop(3);
Plotdata(bigcounter,13)=ductmiddle(3);
Plotdata(bigcounter,14)=ductbottom(3);
Plotdata(bigcounter,15)=sfcduct;
Plotdata(bigcounter,16)=Presstop;
Plotdata(bigcounter,17)=Pressmid;
Plotdata(bigcounter,18)=Tmid;
Plotdata(bigcounter,19)=Dewmid;
Plotdata(bigcounter,20)=Mtop;
Plotdata(bigcounter,21)=Mmid;
Plotdata(bigcounter,22)=pres(1);
Plotdata(bigcounter,23)=drct(1);
Plotdata(bigcounter,24)=sknt(1);
Plotdata(bigcounter,25)=ducttop(1)-ductbottom(1);
Plotdata(bigcounter,26)=ducttop(2)-ductbottom(2);
Plotdata(bigcounter,27)=ducttop(3)-ductbottom(3);
Plotdata(bigcounter,28)=Mtop2;
Plotdata(bigcounter,29)=Mmid2;
Plotdata(bigcounter,30)=Mtop3;
Plotdata(bigcounter,31)=Mmid3;
Plotdata(bigcounter,32)=Mmid-Mtop;
Plotdata(bigcounter,33)=Mmid2-Mtop2;
Plotdata(bigcounter,34)=Mmid3-Mtop3;
Plotdata(bigcounter,35)=(Mmid-Mtop)/(ducttop(1)-ductmiddle(1));
Plotdata(bigcounter,36)=(Mmid2-Mtop2)/(ducttop(2)-ductmiddle(2));
Plotdata(bigcounter,37)=(Mmid3-Mtop3)/(ducttop(3)-ductmiddle(3));
Plotdata(bigcounter,38)=M(1);
if Plotdata(bigcounter,15)==1 %finds M deficit
    Plotdata(bigcounter,39) = M(1)-Mtop;
else
    Plotdata(bigcounter,39) = NaN;
end
```

```
    %Check for the effective "end-of-file"
    if line == -1
        break
    end
end

fclose(fid_in); % --- end of sounding "decoder" portion

%  prepare the name for the ".mat" file
%  Logic:  find the "/"s and ".", so we can use the first part of the
name.
%
index1=find(filename == '/');           %  find the "/" in the name
if length(index1) == 0                  %  if no "/" in name
    first=1;
else
    iend=length(index1);                 %  the last "/"
    first=index1(iend)+1;                %  first character in matfile
name
end
index2=find(filename == '.');
last=index2-1;                          %  use characters before the "."
matfile=filename(1,first:last);
%clear index1 index2 first last iend ans filename jo iline
%
eval(['save ' matfile] )
%
disp('".mat" file has been written to your current directory.')
toc
```

B. MATLAB PROGRAM TO CALCULATE MODIFIED REFRACTIVITY

```
function [M,N] = m_n_profile(pres,tmpc,relh,hght)
%
%  Purpose: Calculates the vertical profiles of Refractive Index, N, and
%           the Modified Refractive Index, M, for input vertical
%           profiles of Pressure, Temperature Relative Humidity and
Height.
%
%  Input:   pres = pressure (millibars)
%           tmpc = air temperature (Celsius)
%           relh = relative humidity (percent, %)
%           hght = height (meters)
%
%  Output:  M = Modified Refractive Index (dimensionless refractivity
units)
%           N = Refractive Index (dimensionless refractivity units)
%
%  Local Variables:
%
%           tmpk = air temperature (Kelvin)
%           e_s  = saturation vapor pressure (millibars)
%           ee   = vapor pressure (millibars)
%
%  References
%     Bean and Dutton, 1968, Equation 1.16.  ... for N
%     Patterson, et al. (1994), Equation 5, p. 9.  ... for M
%     Bolton, Monthly Weather Review, 1980.  ... for saturation vapor
pres
%     Huschke, Glossary of Meteorology, 1959, p. 477.  ... for vapor
pressure
%
%  History
%     Version 1.0  17 July 2001
%     Mary S. Jordan
%     Dept. of Meteorology, Naval Postgraduate School, Monterey, CA
%  -------------------------------------------------------------------

%    ... convert to temperature to Kelvin
tmpk = tmpc+273.15;

%   ... compute saturation vapor pressure, e_s
e_s = 6.112*exp((17.67 .* tmpc)./(tmpc+243.5));

%    ... compute vapor pressure, ee
ee = (relh ./ 100.) .* e_s;

%    ... compute Refractive Index, N, and Modified Refractive Index, M
%
N = (77.6*pres./tmpk) - (5.6*ee./tmpk) + (3.75e5*ee./(tmpk.^2));
M = N + 157*hght./1000;

%  ----------------------- end of function ----------------------------
```

C. MATLAB POGRAM TO CALCULATE POTENTIAL TEMPERATURE AND SPECIFIC HUMIDITY

```
function [thta,q] = theta_q(pres,tmpc,relh)
%
%  function [thta,q] = theta_q(pres,tmpc,relh)
%
%  written by:  Mary Jordan, NPS Meteorology Dept, 10/9/96
%
%  Purpose: Calculates Potential Temperature (thta) and
%       Specific Humidity (q)
%
%  Reference:  Atmospheric Science by Wallace & Hobbs, 1977, Academic
Press
%
%  Input:   pres = Pressure (mb)
%       tmpc = Air Temperature (C)
%       relh = Relative Humidity (%)
%
%  Output:  thta = Potential Temperature (K)
%          q = Specific Humidity (g/kg)
%
% ------------------------------------------------------------


%
% define local constants for thermodynamic equations:
    p0=1000.;R=287.;cp=1004.;L=2.5e6;
%
tmpk = tmpc+273.155;                    % convert to tmpc to Kelvin
%
e_s = 6.1078*exp((17.26939.*tmpc)./(tmpc+237.3));   % saturation vapor
pressure
ee = (relh ./ 100.) .* e_s;                               % vapor pressure
%
w = 0.622 * (ee ./ (pres - ee));                  % mixing ratio (kg/kg)
q_kg = w ./ (1.0 + w);                            % specific humidity
(kg/kg)
%
q=q_kg*1000;                            % specific humidity (g/kg)
%
thta = tmpk .* ((p0 ./ pres).^(R/cp));            % Potential Temperature
(K)

%----------------------     END   ---------------------------
```

D. MATLAB CODE TO FIND STATISTICS

```
x=length(data(:,1)); % number of rows
temp1=0;%temperory variables
temp2=0;
temp3=0;
tmp1=0;
tmp2=0;
tmp3=0;
tempmin1=0;
tempmin2=0;
tempmin3=0;
temp=0;

%finds elevation and sf duct frequencies
counter = 1;
ducts1=0;
for i=1:x
    if data(counter,6)>0
        ducts1=ducts1+1;
    end
    counter=counter+1;
end

percent1duct=(ducts1/x)*100;
table=[];
table(1,1)=percent1duct;
counter = 1;
ducts2=0;

for i=1:x
    if data(counter,9)>0
        ducts2=ducts2+1;
    end
    counter=counter+1;
end

percent2duct=(ducts2/x)*100;
table(1,2)=percent2duct;
counter = 1;
ducts3=0;

for i=1:x
    if data(counter,12)>0
        ducts3=ducts3+1;
    end
    counter=counter+1;
end

percent3duct=(ducts3/x)*100;
table(1,3)=percent3duct;
```

```
%finds frequency of day duct1
counter=1;
dayduct1=0;
day=0;
for i=1:x
    if data(counter,3)==1200
        day=day+1;
    end
    if data(counter,3)==1200 && data(counter,6)>0
        dayduct1=dayduct1+1;
    end
    counter=counter+1;
end
percent1ductday=(dayduct1/day)*100;
table(2,1)=percent1ductday;

%finds frequencu of night duct1
counter=1;
nightduct1=0;
night=0;
for i=1:x
    if data(counter,3)==0
        night=night+1;
    end
    if data(counter,3)==0 && data(counter,6)>0
        nightduct1=nightduct1+1;
    end
    counter=counter+1;
end
percent1ductnight=(nightduct1/night)*100;
table(3,1)=percent1ductnight;

%finds frequency of day duct2
counter=1;
dayduct2=0;
day=0;
for i=1:x
    if data(counter,3)==1200
        day=day+1;
    end
    if data(counter,3)==1200 && data(counter,9)>0
        dayduct2=dayduct2+1;
    end
    counter=counter+1;
end
percent2ductday=(dayduct2/day)*100;
table(2,2)=percent2ductday;

%finds frequency of night duct2
counter=1;
nightduct2=0;
night=0;
for i=1:x
    if data(counter,3)==0
        night=night+1;
```

```
    end
    if data(counter,3)==0 && data(counter,9)>0
        nightduct2=nightduct2+1;
    end
    counter=counter+1;
end
percent2ductnight=(nightduct2/night)*100;
table(3,2)=percent2ductnight;

%finds frequency of day duct3
counter=1;
dayduct3=0;
day=0;
for i=1:x
    if data(counter,3)==1200
        day=day+1;
    end
    if data(counter,3)==1200 && data(counter,12)>0
        dayduct3=dayduct3+1;
    end
    counter=counter+1;
end
percent3ductday=(dayduct3/day)*100;
table(2,3)=percent3ductday;

%finds frequency of night duct3
counter=1;
nightduct3=0;
night=0;
for i=1:x
    if data(counter,3)==0
        night=night+1;
    end
    if data(counter,3)==0 && data(counter,12)>0
        nightduct3=nightduct3+1;
    end
    counter=counter+1;
end
percent3ductnight=(nightduct3/night)*100;
table(3,3)=percent3ductnight;

%find mean height of first duct
counter = 1;
j=1;
for i=1:x
    if data(counter,6)>0
        temp1(j)=data(counter,6);
        j=j+1;
    end
    counter=counter+1;
end
table(4,1)=mean(temp1);
```

```
%find mean height of second duct
counter = 1;
j=1;
for i=1:x
    if data(counter,9)>0
        temp2(j)=data(counter,9);
        j=j+1;
    end
    counter=counter+1;
end
table(4,2)=mean(temp2);

%find mean height of third duct
counter = 1;
j=1;
for i=1:x
    if data(counter,12)>0
        temp3(j)=data(counter,12);
        j=j+1;
    end
    counter=counter+1;
end
table(4,3)=mean(temp3);

% find medians of ducts
table(6,1)=median(temp1);
table(6,2)=median(temp2);
table(6,3)=median(temp3);

% compute 25th percentile (first quartile) for duct1
table(5,1) = median(temp1(find(temp1<median(temp1))));

% compute 75th percentile (third quartile) for duct1
table(7,1) = median(temp1(find(temp1>median(temp1))));

% compute 25th percentile (first quartile) for duct2
table(5,2) = median(temp2(find(temp2<median(temp2))));

% compute 75th percentile (third quartile) for duct2
table(7,2) = median(temp2(find(temp2>median(temp2))));

% compute 25th percentile (first quartile) for duct1
table(5,3) = median(temp3(find(temp3<median(temp3))));

% compute 75th percentile (third quartile) for duct1
table(7,3) = median(temp3(find(temp3>median(temp3))));

% standard deviations of ducts

table(8,1)=std(temp1);
table(8,2)=std(temp2);
table(8,3)=std(temp3);
```

```
% find mean, median and std. dev. of thickness
% duct1
counter = 1;
j=1;
temp1=0;
for i=1:x
    if data(counter,25)>0
        temp1(j)=data(counter,25);
        j=j+1;
    end
    counter=counter+1;
end
table(9,1)=mean(temp1);
table (11,1)=median(temp1);
table(13,1)=std(temp1);

% compute 25th percentile (first quartile) for duct1
table(10,1) = median(temp1(find(temp1<median(temp1))));

% compute 75th percentile (third quartile) for duct1
table(12,1) = median(temp1(find(temp1>median(temp1))));

%duct2
counter = 1;
j=1;
temp2=0;
for i=1:x
    if data(counter,26)>0
        temp2(j)=data(counter,26);
        j=j+1;
    end
    counter=counter+1;
end
table(9,2)=mean(temp2);
table (11,2)=median(temp2);
table(13,2)=std(temp2);

% compute 25th percentile (first quartile) for duct2
table(10,2) = median(temp2(find(temp2<median(temp2))));

% compute 75th percentile (third quartile) for duct2
table(12,2) = median(temp2(find(temp2>median(temp2))));

%duct3
counter = 1;
j=1;
temp3=0;
for i=1:x
    if data(counter,27)>0
        temp3(j)=data(counter,27);
        j=j+1;
    end
    counter=counter+1;
end
```

```
table(9,3)=mean(temp3);
table (11,3)=median(temp3);
table(13,3)=std(temp3);

% compute 25th percentile (first quartile) for duct3
table(10,3) = median(temp3(find(temp3<median(temp3))));

% compute 75th percentile (third quartile) for duct3
table(12,3) = median(temp3(find(temp3>median(temp3))));

% frequency of surface duct
counter=1;
j=1;
temp=0;
for i=1:x
    if data(counter,7)==data(counter,8) && data(counter,7)>0
    temp(j)=data(counter,6);
    j=j+1;
    end
    counter=counter+1;
end
a=length(temp);
table(1,4)=(a/x)*100; %sf duct in all day
table(4,4)=mean(temp);
table (6,4)=median(temp);
table(8,4)=std(temp);

% compute 25th percentile (first quartile) for duct1
table(5,4) = median(temp(find(temp<median(temp))));

% compute 75th percentile (third quartile) for duct1
table(7,4) = median(temp(find(temp>median(temp))));

% find mean, median and std. dev. of thickness
% surface duct
counter = 1;
j=1;
temp=0;
for i=1:x
    if data(counter,15)==1 && data(counter,25)>0
        temp(j)=data(counter,25);
        j=j+1;
    end
    counter=counter+1;
end
table(9,4)=mean(temp);
table (11,4)=median(temp);
table(13,4)=std(temp);

% compute 25th percentile (first quartile) for surface duct
table(10,4) = median(temp1(find(temp1<median(temp))));

% compute 75th percentile (third quartile) for surface duct
table(12,4) = median(temp1(find(temp1>median(temp))));
```

```
counter=1;
j=1;
temp=0;
for i=1:x
    if data(counter,3)==1200....
        && data(counter,7)==data(counter,8) && data(counter,7)>0
    temp(j)=data(counter,7);
    j=j+1;
    end
    counter=counter+1;
end
a=length(temp);
table(2,4)=(a/day)*100; % sf duct in day

counter=1;
j=1;
temp=0;
for i=1:x
    if data(counter,3)==0....
        && data(counter,7)==data(counter,8) && data(counter,7)>0
    temp(j)=data(counter,7);
    j=j+1;
    end
    counter=counter+1;
end
a=length(temp);
table(3,4)=(a/night)*100; % sf duct in night

% finds mean, median, first and second quartiles
% std. deviation of strengt of ducts
% First duct
counter = 1;
j=1;
for i=1:x
    if data(counter,32)>0
        tmp1(j)=data(counter,32);
        j=j+1;
    end
    counter=counter+1;
end
table(14,1)=mean(tmp1);
table (16,1)=median(tmp1);
table(18,1)=std(tmp1);
% compute 25th percentile (first quartile) for duct1
table(15,1) = median(tmp1(find(tmp1<median(tmp1))));

% compute 75th percentile (third quartile) for duct1
table(17,1) = median(tmp1(find(tmp1>median(tmp1))));

% finds mean, median, first and second quartiles
% std. deviation of strengt of ducts
% Second duct
counter = 1;
j=1;
for i=1:x
```

```
    if data(counter,33)>0
        tmp2(j)=data(counter,33);
        j=j+1;
    end
    counter=counter+1;
end
table(14,2)=mean(tmp2);
table (16,2)=median(tmp2);
table(18,2)=std(tmp2);
% compute 25th percentile (first quartile) for duct2
table(15,2) = median(tmp2(find(tmp2<median(tmp2))));

% compute 75th percentile (third quartile) for duct2
table(17,2) = median(tmp2(find(tmp2>median(tmp2))));

% finds mean, median, first and second quartiles
% std. deviation of strengt of ducts
% Third duct
counter = 1;
j=1;
temp3=0;
for i=1:x
    if data(counter,34)>0
        tmp3(j)=data(counter,34);
        j=j+1;
    end
    counter=counter+1;
end
table(14,3)=mean(tmp3);
table (16,3)=median(tmp3);
table(18,3)=std(tmp3);
% compute 25th percentile (first quartile) for duct3
table(15,3) = median(tmp3(find(tmp3<median(tmp3))));

% compute 75th percentile (third quartile) for duct3
table(17,3) = median(tmp3(find(tmp3>median(tmp3))));


% finds mean, median, first and second quartiles
% std. deviation of strengt gradient of ducts
% First duct
counter = 1;
j=1;
tmp1=0;
for i=1:x
    if data(counter,35)>0
        tmp1(j)=data(counter,35);
        j=j+1;
    end
    counter=counter+1;
end
table(19,1)=mean(tmp1);
table (21,1)=median(tmp1);
table(23,1)=std(tmp1);
```

```
% compute 25th percentile (first quartile) for duct1
table(20,1) = median(tmp1(find(tmp1<median(tmp1))));

% compute 75th percentile (third quartile) for duct1
table(22,1) = median(tmp1(find(tmp1>median(tmp1))));

% finds mean, median, first and second quartiles
% std. deviation of strengt gradient of ducts
% Second duct
counter = 1;
j=1;
tmp2=0;
for i=1:x
    if data(counter,36)>0
        tmp2(j)=data(counter,36);
        j=j+1;
    end
    counter=counter+1;
end
table(19,2)=mean(tmp2);
table (21,2)=median(tmp2);
table(23,2)=std(tmp2);
% compute 25th percentile (first quartile) for duct2
table(20,2) = median(tmp2(find(tmp2<median(tmp2))));

% compute 75th percentile (third quartile) for duct2
table(22,2) = median(tmp2(find(tmp2>median(tmp2))));

% finds mean, median, first and second quartiles
% std. deviation of strengt gradient of ducts
% Third duct
counter = 1;
j=1;
tmp3=0;
for i=1:x
    if data(counter,37)>0
        tmp3(j)=data(counter,37);
        j=j+1;
    end
    counter=counter+1;
end
table(19,3)=mean(tmp3);
table (21,3)=median(tmp3);
table(23,3)=std(tmp3);
% compute 25th percentile (first quartile) for duct3
table(20,3) = median(tmp3(find(tmp3<median(tmp3))));

% compute 75th percentile (third quartile) for duct3
table(22,3) = median(tmp3(find(tmp3>median(tmp3))));
```

```
% finds mean, median, first and second quartiles
% std. deviation of strengt of ducts
% surface ducts
counter = 1;
j=1;
tmp1=0;
for i=1:x
if data(counter,15)==1
    if data(counter,32)>0
        tmp1(j)=data(counter,32);
        j=j+1;
    end
end
    counter=counter+1;

end
table(14,4)=mean(tmp1);
table (16,4)=median(tmp1);
table(18,4)=std(tmp1);
% compute 25th percentile (first quartile) for duct1
table(15,4) = median(tmp1(find(tmp1<median(tmp1))));

% compute 75th percentile (third quartile) for duct1
table(17,4) = median(tmp1(find(tmp1>median(tmp1))));

% finds mean, median, first and second quartiles
% std. deviation of strength GRADIENT of ducts
% surface ducts
counter = 1;
j=1;
tmp1=0;
for i=1:x
if data(counter,15)==1
    if data(counter,35)>0
        tmp1(j)=data(counter,35);
        j=j+1;
    end
end
    counter=counter+1;
end
table(19,4)=mean(tmp1);
table (21,4)=median(tmp1);
table(23,4)=std(tmp1);
% compute 25th percentile (first quartile) for duct1
table(20,4) = median(tmp1(find(tmp1<median(tmp1))));

% compute 75th percentile (third quartile) for duct1
table(22,4) = median(tmp1(find(tmp1>median(tmp1))));

% finds mins and maxs of first duct
counter = 1;
j=1;
tempmin1=0;
tempmax1=0;
```

```
for i=1:x
    if data(counter,8)~=0

        tempmin1(j)=data(counter,8);
        tempmax1(j)=data(counter,6);
        j=j+1;

    end
    counter=counter+1;
end
table(24,1)=min(tempmin1);
table(25,1)=max(tempmax1);

% find mins and maxs of second duct
counter = 1;
j=1;
tempmin2=0;
tempmax2=0;
for i=1:x
    if data(counter,11)~=0

        tempmin2(j)=data(counter,11);
        tempmax2(j)=data(counter,9);
        j=j+1;

    end
    counter=counter+1;
end
table(24,2)=min(tempmin2);
table(25,2)=max(tempmax2);

% find mins and maxs of third duct
counter = 1;
j=1;
tempmin3=0;
tempmax3=0;
for i=1:x
    if data(counter,14)~=0

        tempmin3(j)=data(counter,14);
        tempmax3(j)=data(counter,12);
        j=j+1;
    end
    counter=counter+1;
end
table(24,3)=min(tempmin3);
table(25,3)=max(tempmax3);

% find mins and maxs of surface duct
counter = 1;
j=1;
tempmin=0;
tempmax=0;
```

```
for i=1:x
    if data(counter,15)==1 && data(counter,8)~=0

        tempmin(j)=data(counter,8);
        tempmax(j)=data(counter,6);
        j=j+1;
    end
    counter=counter+1;
end
table(24,4)=min(tempmin);
table(25,4)=max(tempmax);

% finds mean, median, first and second quartiles
% std. deviation of Mdeficit of
% surface ducts
counter = 1;
j=1;
tempdeficit=0;
for i=1:x
    if data(counter,39)> 0
        tempdeficit(j)=data(counter,39);
        j=j+1;
    end
    counter=counter+1;
end
table(26,4)=mean(tempdeficit);
table (28,4)=median(tempdeficit);
table(30,4)=std(tempdeficit);

% compute 25th percentile (first quartile) for duct1
table(27,4) =
median(tempdeficit(find(tempdeficit<median(tempdeficit))));

% compute 75th percentile (third quartile) for duct1
table(29,4) =
median(tempdeficit(find(tempdeficit>median(tempdeficit))));

%Finds mean, median, lower and higher quartile and std. deviation of
%surface pressure if there is a duct
counter = 1;
j=1;
temp=0;
for i=1:x
    if data(counter,6)> 0
        temp(j)=data(counter,22);
        j=j+1;
    end
   counter=counter+1;
end

table(31,1)=mean(temp);
table (33,1)=median(temp);
table(35,1)=std(temp);
```

```
% compute 25th percentile (first quartile) for duct1
table(32,1) = median(temp(find(temp<median(temp))));

% compute 75th percentile (third quartile) for duct1
table(34,1) = median(temp(find(temp>median(temp))));

%Finds mean, median, lower and higher quartile and std. deviation of
%surface pressure if there is  no duct
counter = 1;
j=1;
temp=0;
for i=1:x
    if data(counter,6)== 0
        temp(j)=data(counter,22);
        j=j+1;
    end
    counter=counter+1;
end

table(31,2)=mean(temp);
table (33,2)=median(temp);
table(35,2)=std(temp);
% compute 25th percentile (first quartile) for duct1
table(32,2) = median(temp(find(temp<median(temp))));

% compute 75th percentile (third quartile) for duct1
table(34,2) = median(temp(find(temp>median(temp))));

%Finds mean, median, lower and higher quartile and std. deviation of
%surface pressure if there is a surfaceduct
counter = 1;
j=1;
temp=0;
for i=1:x
    if data(counter,15)==1
        temp(j)=data(counter,22);
        j=j+1;
    end
    counter=counter+1;
end

table(31,3)=mean(temp);
table (33,3)=median(temp);
table(35,3)=std(temp);
% compute 25th percentile (first quartile) for duct1
table(32,3) = median(temp(find(temp<median(temp))));

% compute 75th percentile (third quartile) for duct1
table(34,3) = median(temp(find(temp>median(temp))));

%//end of file
```

E. MATLAB CODE TO FIND DUCTS MONTH-BY-MONTH

```
%finds ducts for january
x=length(data(:,1));
counter = 1;
countermonth =1;
month1=[];
for i=1:x
    temp = num2str(data(counter,2));
    tempcpr= temp==' 01  ';
    if tempcpr(2)==1 && tempcpr(3)==1
        month1(countermonth,:)= data(counter,:);
        countermonth = countermonth + 1;
    end
    counter = counter + 1;
end
%finds ducts for february
x=length(data(:,1));
counter = 1;
countermonth =1;
month2=[];
for i=1:x
    temp = num2str(data(counter,2));
    tempcpr= temp==' 02  ';
    if tempcpr(2)==1 && tempcpr(3)==1
        month2(countermonth,:)= data(counter,:);
        countermonth = countermonth + 1;
    end
    counter = counter + 1;
end
%finds ducts for march
x=length(data(:,1));
counter = 1;
countermonth =1;
month3=[];
for i=1:x
    temp = num2str(data(counter,2));
    tempcpr= temp==' 03  ';
    if tempcpr(2)==1 && tempcpr(3)==1
        month3(countermonth,:)= data(counter,:);
        countermonth = countermonth + 1;
    end
    counter = counter + 1;
end
%finds ducts for april
x=length(data(:,1));
counter = 1;
countermonth =1;
month4=[];
for i=1:x
    temp = num2str(data(counter,2));
    tempcpr= temp==' 04  ';
    if tempcpr(2)==1 && tempcpr(3)==1
        month4(countermonth,:)= data(counter,:);
        countermonth = countermonth + 1;
```

```
    end
    counter = counter + 1;
end
%finds ducts for may
x=length(data(:,1));
counter = 1;
countermonth =1;
month5=[];
for i=1:x
    temp = num2str(data(counter,2));
    tempcpr= temp==' 05  ';
    if tempcpr(2)==1 && tempcpr(3)==1
        month5(countermonth,:)= data(counter,:);
        countermonth = countermonth + 1;
    end
    counter = counter + 1;
end
%finds ducts for june
x=length(data(:,1));
counter = 1;
countermonth =1;
month6=[];
for i=1:x
    temp = num2str(data(counter,2));
    tempcpr= temp==' 06  ';
    if tempcpr(2)==1 && tempcpr(3)==1
        month6(countermonth,:)= data(counter,:);
        countermonth = countermonth + 1;
    end
    counter = counter + 1;
end
%finds ducts for july
x=length(data(:,1));
counter = 1;
countermonth =1;
month7=[];
for i=1:x
    temp = num2str(data(counter,2));
    tempcpr= temp==' 07  ';
    if tempcpr(2)==1 && tempcpr(3)==1
        month7(countermonth,:)= data(counter,:);
        countermonth = countermonth + 1;
    end
    counter = counter + 1;
end
%finds ducts for august
x=length(data(:,1));
counter = 1;
countermonth =1;
month8=[];
for i=1:x

    temp = num2str(data(counter,2));
    tempcpr= temp==' 08  ';
    if tempcpr(2)==1 && tempcpr(3)==1
```

```
        month8(countermonth,:)= data(counter,:);
        countermonth = countermonth + 1;
    end
    counter = counter + 1;
end
%finds ducts for september
x=length(data(:,1));
counter = 1;
countermonth =1;
month9=[];
for i=1:x
    temp = num2str(data(counter,2));
    tempcpr= temp==' 09  ';
    if tempcpr(2)==1 && tempcpr(3)==1
        month9(countermonth,:)= data(counter,:);
        countermonth = countermonth + 1;
    end
    counter = counter + 1;
end
%finds ducts for october
x=length(data(:,1));
counter = 1;
countermonth =1;
month10=[];
for i=1:x
    temp = num2str(data(counter,2));
    tempcpr= temp==' 10  ';
    if tempcpr(2)==1 && tempcpr(3)==1
        month10(countermonth,:)= data(counter,:);
        countermonth = countermonth + 1;
    end
    counter = counter + 1;
end
%finds ducts for november
x=length(data(:,1));
counter = 1;
countermonth =1;
month11=[];
for i=1:x
    temp = num2str(data(counter,2));
    tempcpr= temp==' 11  ';
    if tempcpr(2)==1 && tempcpr(3)==1
        month11(countermonth,:)= data(counter,:);
        countermonth = countermonth + 1;
    end
    counter = counter + 1;
end
%finds ducts for december
x=length(data(:,1));
counter = 1;
countermonth =1;
month12=[];
for i=1:x
    temp = num2str(data(counter,2));
    tempcpr= temp==' 12  ';
```

```
    if tempcpr(2)==1 && tempcpr(3)==1
        month12(countermonth,:)= data(counter,:);
        countermonth = countermonth + 1;
    end
    counter = counter + 1;
end
%//end of file
```

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