ECE 5635 Radar Systems: Midterm Design Project

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Introduction

The objective of this report is to detail the design capabilities, explain reasoning, and define the limitations of the hypothetical radar design system problem for the ECE 5635 midterm exam. The hypothetical design is for a customer who desires to build a radar system for an airport that services aircraft ranging from medium-sized commercial aircraft to small private planes. The design is largely open ended; however, the design must operate in the C-band (4 to 8 GHz), transmit 50kW of maximum power, and use a mechanically rotated dish that rotates around a vertical axis. Also, the noise temperature of the receiver cannot be better than 300K. Using the radar equation (POMR Eqn 2.11), derived from the Friis transmission equation, the number of possible areas of improvement are limited given these constraints.

Other important constraints or guidelines that are taken into account are: the RCS ranging from roughly 1 to 10m^2 based on the aircraft; the maximum aircraft velocity is 800km/hr, aircraft that are landing typically descend at an angle of 3^o; aircraft altitude will not exceed 10km; commercial aircraft are expected to accurately report their altitude to the air traffic control; and a larger aircraft should be detected with a P_D=0.9 and P_{FA}=10^{-8} at a range of 200km, while smaller aircraft should similarly be detectable at 100km. It is assumed that aircraft flying below 10km in altitude and with 15km of the airport will be expected to be taking off or landing, such that aircraft at high altitudes over the airport may not be tracked due to antenna beamwidth (BW) constraints. Losing coverage in this condition and creating a limited cone of silence is deemed acceptable. Further assumptions, constraints, or parameters will be outlined in later sections of the report as deemed necessary.

The objective of this radar system is to provide search capabilities that can detect medium-sized aircraft up to 200km from the airport and also provide tracking capabilities that can closely follow an approaching aircraft nearly to the point of landing. A goal for the system is that the refresh rate will be high enough that even the fastest aircraft will not be able to move more than one range gate between updates. The goal is to design a single dish system that can perform both track and search. To get a better understanding of acceptable and realistic parameter ranges in aviation, a US Airways commercial airline pilot was interviewed. Python and MATLAB scripts were written to analyze the proposed system, make rapid design iterations, and generate plots.

Design

As mentioned above, the adjustable design parameters available to optimize the system are limited. Since the power transmitted is fixed to 50kW, transmitted frequency is confined to C-band, RCS is defined, maximum detectable range is specified, noise temperature of the receiver cannot be improved to be less than 300K, and there are inevitable system losses involved, the major parameters available to tweak are antenna gain, pulse integration gain, receiver bandwidth, PRF, and dish RPM.

To begin the design process, the long range search capability is considered first in the situation that will be most difficult to detect, which we predict will be detecting a commercial airliner (RCS = ~$10m^2$) at a max distance of 200km due to the $1/R^4$ factor in the radar equation. This project specifies that a small aircraft (RCS=~$1m^2$) should also be detectable at 100km. However, a decrease in the RCS by a factor of 10 and a decrease in the range by a factor of 2 results in a +2dB increase in P_r, such that if the first case is detectable, then smaller aircraft at closer distance will also be detectable.

The initial assumed operational frequency will be 4.0GHz (λ=0.075m) to maximize power received in the C-band using the radar equation. As shown in Figure 1, to obtain an unambiguous detectable range of 200km using a single PRF, the PRF must be no larger than 750 Hz. Aircraft are required to keep a visual watch out for nearby aircraft and have built-in collision avoidance alarms, so we will assume a range resolution of 500m, which corresponds to a pulse width τ=3.33e-06s, and B = $1.4/\tau$ = 420kHz.

It is specified that aircraft will be no higher than 10km in altitude and will descend for landing at a 3^o angle. Conveniently, R = 10km/tan(3^o) = 191km, as shown in Figure 2, which is nearly our maximum detectable range. It is assumed that landing aircraft are the main priority, and any landing aircraft at or below 10km in altitude must begin descending 190km from the airport to avoid exceeding the specified 3^o angle of descent. We will also assume that a medium or large sized aircraft will be flying above 2km in altitude if it is farther than 30km from the airport, since most airliners cruise at an altitude above 3km (10,000ft). These assumptions lead us to a required vertical BW of θ_V=arctan(8km/200km) = 2.3^o, corresponding to a D_v = 2.4m dish diameter in the vertical direction. The antenna will also be fitted with an electric motor that allows it to change its orientation in the vertical direction to scan upwards and downwards if needed. This can be used to shrink the cone of silence for search of higher altitude targets at a closer range or to implement a more sophisticated search algorithm that uses multiple vertical beam positions to search a larger area. However, this BW assumption is broken if the aircraft circles the airport at a closer range while descending. In addition, the cone of silence is very large, which will be addressed later in the report.

The parabolic dish antenna's horizontal BW was chosen to be θ_H= 0.7^o, similar to that chosen in the X-band radar example in the Week 5 lecture, and with the goal of maximizing dish gain to meet the required SNR margin. This horizontal antenna BW corresponds to approximately 514 range bins when the antenna is rotated 360^o around the vertical axis. Using the equation G = 33,000/(θ_V*θ_H), the gain of this system's parabolic dish antenna is G = 33,000/(2.3^o*0.7^o) = 43.1dB. The horizontal dimension of this parabolic dish antenna is D_H = 8.0m, which is within reasonable means for rotation.

Since the design parameters make it challenging to meet the detection margin, maximum antenna gain is desired. Smaller BW in both the vertical and horizontal directions leads to improved gain. Due to the limitations on reducing BW as shown in the calculations above, the only choice is to restrict horizontal BW. However, this presents a design tradeoff because smaller BW leads to a lower required dish rotation RPM, which slows the refresh rate of the radar system. For the first iteration, horizontal BW will be made to $\theta_V=2.3^o$ in accordance with the value used in Week 5's lecture on slide 56.

We are assuming a system that has a specified 10dB RF, loss as well as 2dB beam shape loss, and 1dB filter mismatch loss in accordance with values used in the X-band radar design example used in Week 5's lecture.

Initially, the proposed design attempted to use a single PRF value to calculate the unambiguous range. At a range of 200km, the unambiguous range calculation yields a PRF=750Hz and a PRI=1/PRF=1.33ms. Given that our design will probably need at least 20 integrated pulses on the target to detect with the proper certainty, required dwell time is at least 26.7ms, which is infeasible due to the horizontal BW constraints, necessary antenna gain, and necessary dish RPM required to track targets.

Instead, the revised design uses a multiple PRF combination to resolve range ambiguity as outlined in the Week 5 lecture supplement for the course. This system transmits 10 pulses with a PRF=8100Hz, 9 pulses with a PRF=7300Hz, and 8 pulses with a PRF = 6500Hz, resulting in 27 pulses per range gate with a dwell time of T_D=3.7ms. This dwell time is 13.8% of that of a single PRF for a target at 200km, while still resolving the target. Duty cycle is 2%, and average transmitted power is 1kW. Coherent integration gain is assumed, and 27 pulses results in an integration gain of 14.3dB. A MATLAB code was written to check for potential aliasing under 200km for this triplet of PRFs. No time differences corresponding to less than 500m resolution occur between the triplets in the desired time frame.

Every radar system desires minimum possible range resolution; however, decreasing range resolution comes with the expense of decreasing pulse width, which increases required receiver bandwidth. Increased receiver bandwidth results in increased noise power levels, which directly decreases the effective SNR. From this analysis, a tradeoff exists between effective noise power and range resolution. This proposed system will attempt to have 420m (1378 feet) range resolution to give a buffer against the 500m estimate that was initially made. Range resolution of 420m results in pulse width τ=2.8e-06s and receiver bandwidth of B_{IF}=0.5MHz. This requirement appears reasonable after speaking with a commercial airline pilot, because pilots are required to keep a visual lookout for nearby aircraft and larger aircraft, and commercial aircraft are equipped with collision avoidance systems that will alert them if another aircraft is that close. In addition, current commercial aircraft tend to follow GPS defined routes with a precision less than 300m.

Given a receiver bandwidth of B_{IF}=0.5MHz and P_{FA}=10-8, the time between false detections is $T_{fa} = 1/(B_{IF}*P_{FA})$ = 200s. This figure should be adequate, since multiple pulses are presumably being reflected off of each target, and all traffic is assumed to be friendly. Conversely, if the radar system was searching for ICBM missiles or incoming enemy aircraft, this T_{fa} would not be acceptable.

With a horizontal BW of θ_H= 0.7° and a dwell time of T_D=3.7ms, the antenna must rotate at an angular velocity of 3.3rad/s, which is equivalent to approximately 31.6rpm. This value seems to be on the upper limit of an acceptable range for dish revolutions per minute; however, it definitely appears to be feasible. Market research shows that a number of real-world systems with an antenna dish on the same order of magnitude as the one proposed in this project operate at 30rpm or above, such as the BAE Systems Artisan 3D radar, AN/MPQ-64 Sentinel radar, and the Selenia RAN-10S / SPS – 774 radar system.

While the position and velocity of a target can be estimated by tracking the changes in distance and direction of the reflected radar pulse, using Doppler shift can provide more accurate information regarding the target's velocity vector. Using the lowest PRF of the triplet that is being used, a PRF=6500Hz corresponds to a maximum Doppler shift of ±PRF/2 = ±3250Hz. This maximum Doppler shift frequency corresponds to the maximum unambiguous velocity, which is calculated to be roughly 438 km/hr. While this value is roughly 55% of the assumed maximum aircraft velocity, the situations of takeoff and landing are where the ability to accurately track aircraft position and velocity are most critical. Presumably, the aircraft will be well below maximum velocity for takeoff and landing, so having the ability to calculate the velocity vector from the measured Doppler shift of a target should be very useful.

When designing a radar system, it is important to take into account physical effects and losses from the real world to accurately calculate the link margin. However, as specified in the project outline, a flat earth is assumed, with no mountains or complicating geographical features, and no source of echoes. We also assume no sources of atmospheric clutter, such as birds, and disregard more complex atmospheric effects such a multipath fading, surface diffraction, atmospheric turbulence, atmospheric refraction, and atmospheric scattering other than what is covered in *F*, the propagation loss factor. Only factors mentioned in class will be taken into consideration.

The effects of water vapor in clean air and rain rates are evaluated. Working at 4.0GHz, the bottom of C-band, is also advantageous because the loss due to rain attenuation increases with frequency within the band. Published charts indicate that at 15°C, 1013 hPa, and 7.5g/m^3, the one-way clean air water vapor loss constant is ~10^{-3} dB/km. For a radar pulse over a 200km range, the loss over two-way propagation will be approximately 0.4dB.

For rain attenuation calculations, it is assumed that the dish is excited with vertically polarized dipole, such that the vertical polarization attenuation coefficients apply. Using Table 4-2 in POMR, we assume a_v = 0.591e-3 and b_v = 1.075 at 4.0GHz. These values yield an attenuation coefficient of α = 2.6e-3 dB/km with rain of 4mm/hr and α = 7.0e-3 dB/km with rain of 10mm/hr. For a radar pulse over a 200km range, the loss over two-way propagation will be approximately 1.0dB for 4mm/hr and 2.8dB for 10mm/hr. The effect of rain on the performance of the system is shown in Figure 3. A more in-depth analysis would also consider situations such a snow, dust, or smoke.

This system works as a line-of-sight microwave radar. According to the lecture notes (Week 5.81), some bending of waves occurs due to refraction, and targets can be detected beyond the physical horizon. Since targets are only being considered in the troposphere (h<10km), it can be assumed that temperature will decrease with altitude and not add additional error. Using the equation on slide 82 of Week 5's lecture, objects below h=2.37km will not be detectable because they are in a shadow in the diffraction non-line of sight region as shown in Figure 4. At a distance of 200km, our antenna is not looking for aircraft below 3km in altitude, as explained above, so this condition does not significantly affect the radar system's performance. Using the same equation, all targets within 130km of the airport will be in the diffraction line-of-sight at an altitude above 1km. Curvature of the earth should not affect the performance of the system if we disregard low-altitude targets at ranges above 130km, as commercial aircraft will be flying at higher altitudes.

To determine whether a target will be reliably detected, the power received must be a certain margin above the noise floor defined by bandwidth of the receiver and the noise temperature of the receiver. More specifically, the voltage signal at the output of the receiver must be above a given threshold set above the additive white Gaussian noise of the system. For the proposed system in this project, the noise level is -146.8dBW. Using Table 3-6 in POMR, an SNR of ~14dB is required to detect a non-fluctuating (SW0) target reliably with a P_D=0.9 and P_{FA}=10^{-8}. However, most targets are more accurately modeled as an SW1 target comprised of many small scatters with dwell-to-dwell fluctuations. Using POMR Table 3-8 and Eqn 3-23, it is shown that the required SNR needed in the SW1 case for P_D=0.9 and P_{FA}=10^{-8} is ~22.4dB. With a noise level of -146.8dBW, the SW0 case requires an approximate Pr of -132.8dBW, and a presumably more accurate SW1 case requires this system to have a Pr at or above -124.4dB for proper detection.

The radar equation (POMR 2.11) is used to determine whether a given case has adequate SNR to be detected at the desired level. Given all of the assumed parameters outlined in this report, a target with RCS=10m^2, h=10km, and R=200km has a SNR of 23.4dBW, as shown in Figure 5, which achieves the specification in what is defined as Case A. In addition, a target with RCS=1m^2, h=10km, and R=100km has an SNR of 25.6dBW, which also passes specification for both the SW0 and SW1 cases in what is defined as Case B.

In the case of rain at 10mm/hr, the target in Case A only has a SNR of ~21.0dB, which misses the margin ~1.4dB, as shown in Figure 3. However, the SNR still results in a P_D=0.865, which is probably acceptable in most cases. When range is reduced to R=~185km, the margin will be reached for P_D=0.9. At the same rain rate, the target in Case B will have a SNR=24.4dB, meeting specification. In the case of rain at 4mm/hr, Case A has SNR of 22.8dB, and Case B has a SNR of 25.3dB, once again meeting specification.

It is assumed that commercial aircraft will accurately report their altitude, but no assumption is made for small aircraft. Given the antenna BW, this system will not accurately track the altitude of the small aircraft. However, there are FAA regulations to prevent small airplanes from harmfully interfering with commercial airport operations. According to the FAA, Class C airspace protects the approach and departure paths from aircraft not under air traffic control below 1.2km in altitude and 18.5km from the airport. All aircraft inside Class C airspace are subject to air traffic control and traffic operating under VFR (visual flight rules) must be in communication with a controller before entering the airspace. When a small aircraft is detected and does not respond to air traffic control, approaching aircraft can be told to keep a VFR lookout for the other airplane.

To improve the system and dramatically reduce the cone of silence above the airport, a second antenna will be added with a $\theta_V=25^o$ and $\theta_H=0.7^o$ to point directly above the 3dB BW of the first antenna, as shown in Figure 2. The antenna dimensions will be 0.225m vertically and 8.0m horizontally, providing 32.8dB gain. With the addition of this second antenna, targets at h=10.0km will be detectable and within the 3dB BW at d=18.7km from the airport, targets at h=5km will be within the 3dB BW at d=9.3km, and a target at h=1.0km, will be within the 3dB BW at d=1.9km. Since vertical BW is much larger for the upper antenna, the RCS=10m^2 target is only detectable within 65km assuming SW1 and 105km assuming SW0, as shown in Figure 6. Similarly, the RCS=1m^2 target is detectable at 35km assuming SW1 and 59km assuming SW0. While larger range is desired, it is beneficial to using wider BW for the upper antenna to minimize the cone of silence near the airport. The pulses of each antenna will be staggered, such that no more than 50kW is being transmitted at any instance. The average power will double with the addition of this second dish, however, that is the cost of increasing the volume of coverage.

As an aside and a cost savings approach, the functions of this radar system could be carried out with GPS devices interfaced with radio transmitters onboard each aircraft. As many commercial airliners already are, each plane could be fitted with a GPS system that interfaces with a computer system and radio transmitter. In an automated process, each aircraft could have a computer that sends the aircraft's location coordinates, velocity, altitude, aircraft type, and any other relevant information to air traffic control frequently. The air traffic control could track the aircraft accurately based on the received data. Since all targets are assumed to be friendly, there is little need to search for unknown targets. A search radar system could be available as a back-up system. However, I understand that this is a project for a radar design course, so this is not an acceptable answer for the midterm.

Conclusion

While the required specifications were challenging, the proposed radar system for this project seems to satisfy the requirements in most of the important cases for aircraft taking off or landing. Optimally, P_t would be increased, maximum range decreased, or more flexibility in frequency would be given to improve performance. The main ways to improve the proposed system would be to still meet required margins, but with greater antenna BW, a slower RPM, and even finer range resolution. To meet specification, antenna BW had to be squeezed farther than may generally be desired in both the horizontal and vertical planes. For this reason, a second antenna dish was added to drastically reduce the size of the cone of silence and provide greater coverage for higher altitude aircraft flying near the airport. In addition, a lower RPM is desired to reduce the risk of mechanical part failure. In addition, the use of an electronically scanned phased array antennas more desirable than the mechanically rotated dishes that were used due to quicker scan time.

No specific cost figures were given in this project, so the notion of cost had to be estimated. An effort was made to design a system that would be fairly cost effective to implement. With more accurate specifications, real-world losses taken into greater consideration, and the ability to use more advanced technologies, a different system may be proposed utilizing either more dishes or multiple radar systems at different locations to provide overlap or different frequencies within the same band. However, given the midterm project requirements and guidelines, it is believed that the system outlined in this report would be a great solution.

Appendix A: Summary of Parameters

	Case A (Commercial Aircraft)	Case B (Small Private Airplane)	Comments
RCS	10 m^2	1 m^2	
Frequency	4.0 GHz	4.0 GHz	
Wavelength	0.075 m	0.075 m	
Max Distance	200 km	100 km	
Max Altitude	10 km	10 km	
Max Range	200.25 km	100.5 km	
Bandwidth (ver)	2.3 degrees	2.3 degrees	
Bandwidth (hor)	0.7 degrees	0.7 degrees	
Dish Diameter (ver)	2.4 m	2.4 m	
Dish Diameter (hor)	8.0 m	8.0 m	
Gain	20,497	20,497	
Gain (dB)	43.1 dB	43.1 dB	
Far-Field Distance	1.7 km	1.7 km	
Integration Pulses	27 pulses	27 pulses	
Noise Temperature	300 K	300 K	
Integration Gain (dB)	14.3 dB	14.3 dB	
IF Bandwidth	0.5 MHz	0.5 MHz	
Pulse Width	2.8e-06 s	2.8e-06 s	
Ave. Time per False Alarm	200 s	200 s	
Range Resolution	420 m	420 m	
Unambiguous Range	>200 km	>200 km	* Using Multiple PRF
PRF	6500, 7300, 8100 Hz	6500, 7300, 8100 Hz	

PRI	0.154, 0.137, 1.23 ms	0.154, 0.137, 1.23 ms	
Max Doppler Freq.	3.25 kHz	3.25 kHz	* Using Lowest PRF
Max Doppler Velocity	439 km/hr	439 km/hr	
Dwell Time	3.7ms	3.7ms	
Clean Water Vapor Loss	~10^-3 dB/km	~10^-3 dB/km	
Rain Attenuation (4mm/hr)	0.00262 dB/km	0.00262 dB/km	
Rain Attenuation (10mm/hr)	0.00702 dB/km	0.00702 dB/km	
Loss Water Vapor Clean Air	0.4 dB at 200 km	0.2 dB at 100 km	
Loss Rain (4mm/hr)	1.1 dB at 200 km	0.5 dB at 100 km	
Loss Rain (10mm/hr)	2.8 dB at 200 km	1.4 dB at 100 km	
Duty Cycle	2%	2%	
Ave. Power Transmitted	1 kW	1 kW	
Antenna Dish RPM	31.6 rpm	31.6 rpm	
System Losses (dB)	10 dB	10 dB	
Beam Shape Loss (dB)	2 dB	2 dB	
Filter Mismatch Loss (dB)	1 dB	1 dB	
Pt (dB)	47.0 dBW	47.0 dBW	
Pr (dB)	-123.4 dBW	-121.2 dBW	
Noise (dB)	-146.8 dBW	-146.8 dBW	
Losses (dB)	13.4 dBW	13.2 dBW	
Margin (dB)	**23.4 dBW**	**25.6 dBW**	*at Max Range for Clean Air
Required SW1 Margin	22.4 dB	22.4 dB	
Required SW0 Margin	~14 dB	~14 dB	
Meets SW1 Margin?	**Yes**	**Yes**	

Table 1: Summary of Radar Design Parameters

Appendix B: Referenced Plots

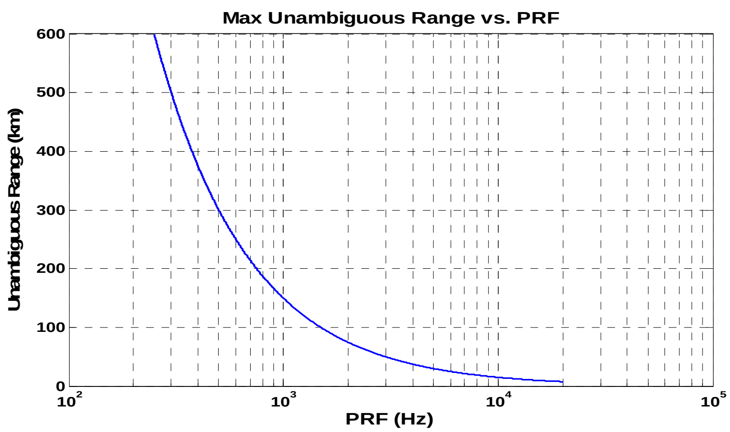

Figure 1: Relationship between Unambiguous Range and PRF

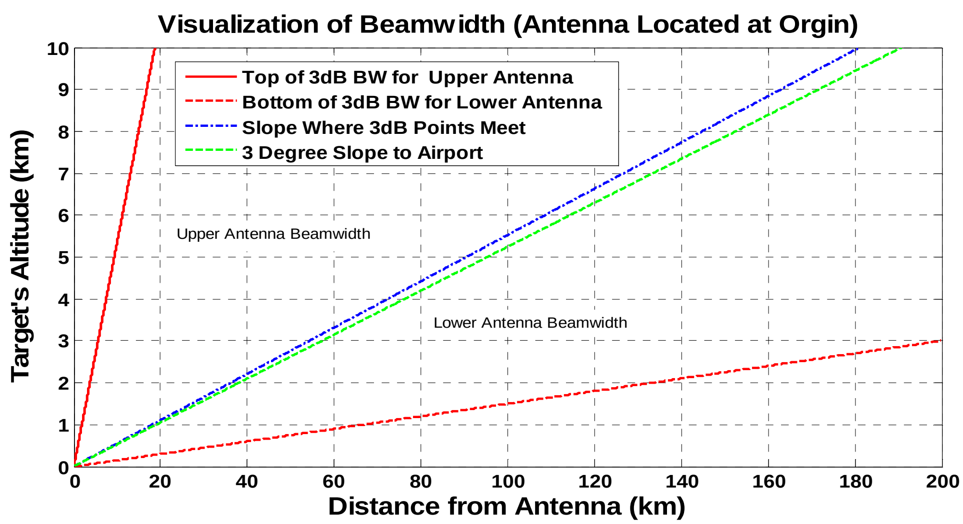

Figure 2: Depiction of Beamwidth Coverage Proposed Dish

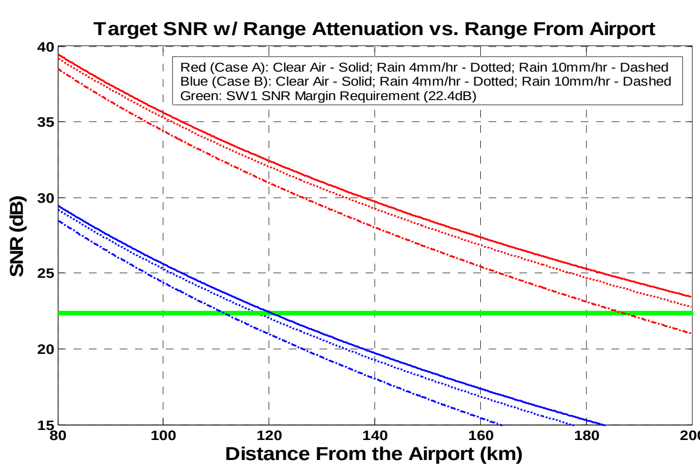

Figure 3: Effects of Rain Attenuation on the Proposed System

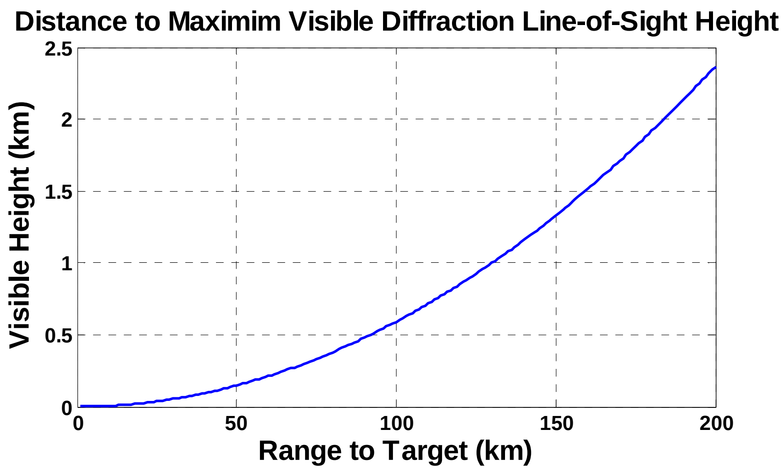

Figure 4: Detectable Height of Targets Over the Horizon

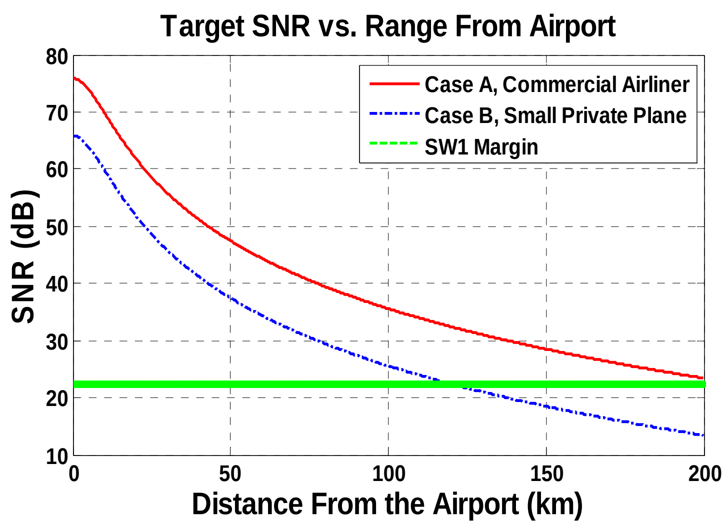

Figure 5: Relationship between SNR and Target's Range from Airport for Lower Antenna

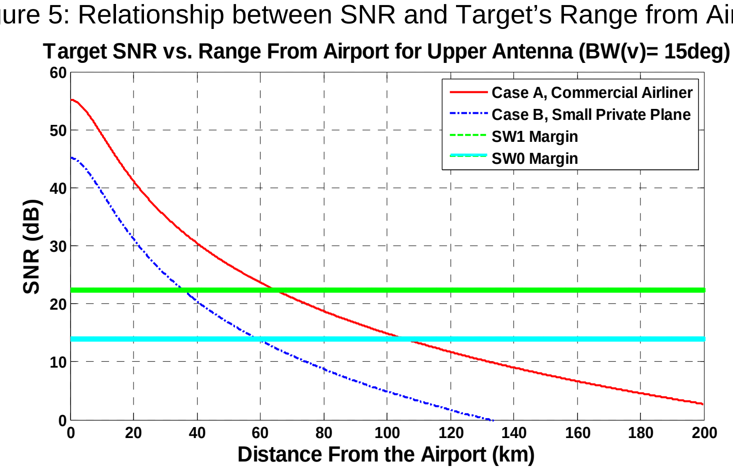

Figure 6: Relationship between SNR and Target's Range from Airport for Upper Antenna

*** Please do not take off points for this sheet exceeding the 10 pages. It is not part of the actual report. I am attaching my analysis code written in Python for your reference in case you have further questions regarding my analysis methods. If you plan to take off points then please do not read beyond this point. Thanks John. ***

```
# John Hodge
# ECE 5635 Midterm Radar Design Analysis Code
# 10/10/13
import math;

# Constant
c = 3*math.pow(10, 8);
Pt = 50000; # Power Transmitted in Watts
Tn = 300; # Noise Temperature in Kelvin
k = 1.38*math.pow(10, -23);
P_fa = math.pow(10, -8);
# PRF = 1500; #
PRF = 6500.0;
bw_v = 2.3; # Vertical   3dB Beamwidth in Degrees
bw_h = 0.7;  # Horizontal 3dB Beamwidth in Degrees
freq = 4.0; # Frequency in GHz

# Function to turn value into dB units
def dB(x):
    return 10*math.log10(x);

# Antenna Design
freq = freq*math.pow(10, 9); # Frequency (converting units)
wl = c/freq;
r_ant = 4; # Antenna Dish Radius in Meters
ant_eff = 0.7;
bw2 = 70*(wl/(2*r_ant));
Ae = math.pi*r_ant*r_ant; # Antenna Effective Area
# gain = 23060.8; #(4*math.pi)*(ant_eff*Ae)/(wl*wl); # Antenna Gain
gain = 33000/(bw_v*bw_h); # Gain using this equation using 3dB beamwidth
gain_dB = dB(gain);
bw = 181.659/math.sqrt(gain); # Beamwidth of the Dish
d = 100000; # Max Radar Range in Meters
h = 10000;
Rd = math.sqrt(d*d+h*h);
R = Rd;
rcs = 1; # RCS Coefficient
Pt_dB = dB(Pt);
farField = 2*(2*r_ant)*(2*r_ant)/wl; # Distance to Far Field for Antenna in Meter
Bn = 0.50*math.pow(10, 6); # Noise Bandwith of Receiver (Hz)
Bn_MHz = Bn / math.pow(10, 6); # Bn in MHz
G_int = 27.0; n = G_int; # Integration Gain / Number of Pulses that Hit Target;
G_int_dB = dB(G_int);
tau = 1.4/Bn;
B_if = Bn;
T_fa = 1.0/(B_if*P_fa);
Ru = c/(2.0*PRF);
fd_max = PRF/2.0; # +or- max doppler shift
duty_cycle = tau*PRF;
P_avg = Pt*tau*PRF;
PRI = 1.0/(PRF);
r_res = (c*tau)/2.0;
vr_max = ((wl*fd_max)/2.0)/0.2778; # Velocity Corresponding to the Max Doppler Shift
Td = n/PRF;
d_v = 75.0*(wl/bw_v);
d_h = 75.0*(wl/bw_h);
```

```
# Rain Attenuation Models at 4 GHz (assuming vertical polarization)
rain_rate = 10; # mm/hr
a = 0.000591;
b = 1.075;
alpha = a*math.pow(rain_rate, b);

# Losses
L_sys_dB = 10;
L_beamsl_dB = 2; # Beam Shape Loss in dB
L_filt_dB = 1; # IF Filter Mismatch Loss
L_wv = 0.001*2*R/1000;
L_ra = alpha*2*R/1000;
# L_atm  # Atmospheric Loss
# ...

L_tot_dB = L_sys_dB + L_beamsl_dB + L_filt_dB + L_wv;

# Output Parameters
Pr = (Pt*(gain*gain)*(wl*wl) * rcs * G_int) / (math.pow(4*math.pi, 3)*math.pow(R,
4));
Pr_dB = dB(Pr) - L_tot_dB;
N = k*Bn*Tn;
N_dB = dB(N);
margin_dB = Pr_dB - N_dB; # Radar Margin

# Display
print 'Parameters :';
print '------------';
print 'Frequency   : ',freq/math.pow(10, 9),'GHz';
print 'Wavelength  : ',wl,'m';
print 'Range to Target : ',round(R/1000, 2),'km at',h/1000,'km altitude
and',d/1000,'km distance.';
print 'BW (vert)   : ',bw_v,'degrees';
print 'BW (hor)    : ',bw_h,'degrees';
print 'Diameter v  : ',round(d_v,1),'m';
print 'Diameter h  : ',round(d_h,1),'m';
# print 'Dish Radius : ',r_ant,'m';
print 'Gain        : ',round(gain, 1);
print 'Gain (dB)   : ',round(gain_dB, 1),'dB';
# print 'Beamwidth   : ',round(bw, 2),'degrees';
# print 'Beamwidth 2 : ',round(bw2, 2),'degrees';
print 'Far-Field Distance  : ',round(farField,1),'m';
# print 'Power Rec.  : ',round(Pr,6),'W';
print 'Integ Gain  : ',round(G_int_dB,1),'dB';
print 'Bandwidth   : ',Bn_MHz,'MHz';
print 'Pulse Width : ',tau,'s';
print 'T False Al  : ',T_fa,'s';
print 'Range Res.  : ',r_res,'m';
print 'Range Unamb : ',round(Ru,1),'m';
print 'PRF         : ',PRF,"Hz";
print 'PRI         : ',round(PRI,6),'s';
print 'Max Doppler : ',fd_max,'Hz';
print 'Vr Max      : ',round(vr_max,1),'km/hr';
print 'Dwell Time  : ',round(Td, 4),'s';
print 'Rain Attenuation : ',round(alpha,5),'dB/km';
print 'Loss Due to Water Vapor in Clean Air : ',round(L_wv,1),'dB at',
round(R/1000,2),'km with rain rate of',rain_rate,'mm/hr';
print 'Loss Due to Rain Attenuation         : ',round(L_ra,1),'dB at',
round(R/1000,2),'km with rain rate of',rain_rate,'mm/hr';

# Display Most Important Parameters
print '\n';
print 'Most Important Parameters :';
```

```
print '-------------------------';
print 'Pt     (dB)               :   ',round(Pt_dB, 1),'dBW';
print 'Pr     (dB)               : ',round(Pr_dB, 1),'dBW';
print 'Noise  (dB)               : ',round(N_dB, 1),'dBW';
print 'Losses (dB)               :   ',round(L_tot_dB, 1),'dBW';
print 'Margin (dB)               :   ',round(margin_dB, 1),'dBW';
print 'Required SW1 Margin (dB) :    22.4 dBW'
print 'Required SW0 Margin (dB) :   ~14.0 dBW'

if (margin_dB >= 22.4):
    print 'SW1 Margin Reached!';
    print 'SW1 Margin Padding :',round(margin_dB-22.4,1),'dB';
else:
    print '!!!!! SW1 Margin Not Reached! !!!!!';
    print 'Missed SW1 Margin By',round(margin_dB-22.4,1),'dB';
```