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Ground Based Radar Design for Intercontinental Ballistic Missile Defense

by

Brian David Egbert

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A creative investigation submitted to the Graduate Faculty
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Ground Based Radar Design for Intercontinental Ballistic Missile Defense Creative Investigation directed by Dr. Don Caughlin

This creative investigation project addresses the requirements for a ground based intercontinental ballistic missile search and track radar system. Several design approaches are discussed along with their advantages and disadvantages. The final design choice is a phased array radar system modeled after the Ballistic Missile Early Warning System (BMEWS) currently in use for national missile defense. The project also includes how the radar was modeled and integrated into a nuclear missile defense simulation. Shortcomings of the current simulation along with areas of potential improvement are also included.

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I. Introduction

This creative investigation focused on the ground based radar portion of a system capable of performing a ground based intercept of an incoming ballistic missile. This system includes a space based sensor system, ground based radar, a battle manager, and a ground based interceptor. This investigation will discuss various approaches to achieving radar requirements within the missile defense system, how the radar segment was modeled, and how the model was applied to a simulation of the entire defense system.

II. Background and Requirements

Within a national missile defense system, the ground-based radar performs three main functions. First the radar system must perform an autonomous search to detect and identify potential threats through surveillance, detection, and discrimination processes. It must then track potential targets and continue to evaluate the potential threat. The information provided by the radar system is used to determine whether or not to commit an interceptor and provides tracking information accurate enough to launch the interceptor. Once an interceptor is committed, the radar continues to provide tracking to the interceptor until it is able to acquire a more accurate fix and track of its own. The radar system continues to track the missile after interception and performs kill assessment.

The necessary range and angular measurement accuracy required to commit an interceptor drive the required power and capabilities of the radar design. The defense system is designed with the intention to destroy any incoming intercontinental ballistic missiles exoatmospherically. This requirement determines how quickly the radar system must detect, identify, and communicate the necessary information to the ground based interceptor, in order to give it enough time and tracking data to reach the incoming missile before it re-enters the atmosphere.

III. The Investigation

There are many different approaches to designing a ground based radar for national missile defense, each with its own advantages and disadvantages. The principal approach in use today is phased array radar, such as PAVE PAWS and the Ballistic Missile Early Warning System (BMEWS) radar. PAVE is an Air Force project name and PAWS stands for Phased Array Warning System (PAVE PAWS). This investigation includes research into five possible radar systems capable of ballistic missile search and track functions with their advantages and disadvantages.

Over-the-Horizon Radar

The first design approach examined is Over-the-Horizon (OTH) Radar. It is essential to detect a potential missile launch as soon as possible to maximize the time to prepare and respond. The curvature of the Earth limits detection time for line-of-sight radar systems, so the ability to detect potential threats beyond the horizon is an incredible advantage. OTH radar is capable of observing below the horizon by the refraction of propagated electromagnetic waves by the Earth's ionosphere, as shown in figure 1. This only occurs in the high frequency (HF) band of 3-30 MHz (Kolosov ix).

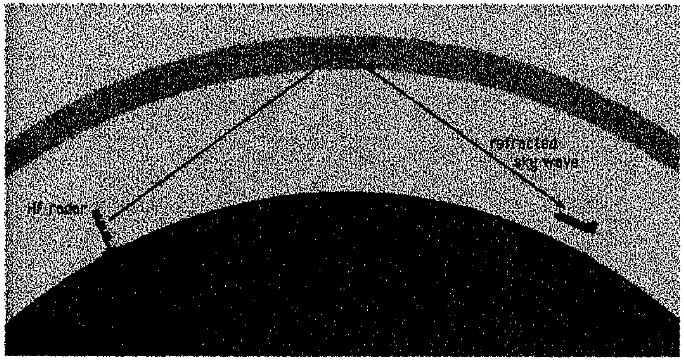

Figure 1. Over-the-Horizon Radar

Radar waves "reflected" off the ionosphere that strike a potential target can either be detected by a separate receiver down range from the transmitter (forward scattering) or by the transmitter site (back scattering) (Kolosov 3). Although the forward scattered signal strength exceeds that of the back scattered, having the transmitter and receiver separated by long distances limits the observable area to the region between the two ground stations. Also, forward scattered wave detection systems cannot determine range or location, only that there is a potential target. Back scattered receivers are capable of predicting range and angular coordinates of potential targets, though accuracy is low.

Irrespective of scatter direction, there is a great deal of interference introduced into the received signals by the ionosphere and ground reflections. Additionally, radio broadcasting systems use the same HF bands and can introduce significant interference. The ionosphere is constantly changing and its properties fluctuating. Due to the ionospheric fluctuations, it is impossible to maintain an adequate signal to noise ratio for any extended period of time or on any particular frequency. Therefore, both transmitter and receiver must have rapid tuning capabilities over a wide operating band to maintain signal reception.

Over-the-Horizon radar has a detection range of 1000-4000 km. OTH radar is useful for aircraft detection and tracking, but for intercontinental ballistic missiles, OTH radar is more useful for detecting ionospheric disturbances caused as the missile leaves the atmosphere. Once the missile goes above the earth's atmosphere, OTH radar is useless since it cannot penetrate the ionosphere.

MMW Radar

To avoid ionospheric refraction and acquire necessary measurement accuracy, a higher transmit frequency must be used. Millimeter-wave (MMW) radar operates in the frequency range of 30-300 GHz. For a given antenna and at these frequencies, beamwidth is narrower, antenna gain is higher, and accuracies are better than obtained by using lower frequencies. However, MMW radar design is driven by high atmospheric loss constraints that limit its range capabilities. Typical clear day atmospheric losses can range from 0.2 to over 20 dB losses per km due to oxygen and water vapor, which is extremely higher than the attenuation at lower frequencies (Currie 9). Negative weather conditions such as rain and fog significantly increase atmospheric losses in MMW frequencies. MMW radar does have many significant uses and applications such as radio astronomy, communications, and missile guidance. However, due to the significant atmospheric losses, an unrealistic power and antenna size would be required to meet intercontinental ballistic missile detection and tracking ranges.

Laser Radar

Laser radar systems are very similar to the MMW radar, but operate at much higher frequencies. Atmospheric attenuation is also very high at these wavelengths, but there are several atmospheric windows where the laser frequency passes through the atmosphere more efficiently. Most laser radar systems are designed at wavelengths of either 1.06 μm or 10.6 μm. Neodymium YAG lasers are used to get the 1.06 μm wavelength and CO_2 lasers are used for the 10.6 μm wavelength (Hovanessian 220). Laser radars are much smaller than conventional radar systems and provide extraordinary range and angular accuracy. Due to the reduced size and the nature of lasers, the radar beamwidth is determined by size of the laser cavity, yielding a very narrow beamwidth. A major drawback of such a narrow beamwidth is the incapability of performing a search for potential targets over any given area. Laser radar must be used in conjunction with other systems capable of searching for targets in order for it to be effective. It is often used as a secondary system to reduce false alarm rates and improve measurement accuracy of other search and track systems.

Rotating Parabolic Radar

Rotating parabolic search radar can perform either two-dimensional or three-dimensional search and track functions. To perform a two-dimensional search, a fan beam is rotated mechanically to scan in all directions (Sabatini 9). The two-dimensional search provides only range and azimuth information of potential targets. Three-dimensional search radar creates a pencil beam in order to provide range, azimuth, and elevation information. The pencil beam can either be electronically scanned or a multiple stack of pencil beams can be created in the elevation direction in order to provide range, azimuth, and elevation data as the radar rotates (Sabatini 11). Mechanically rotated radar has some inherent disadvantages such as mechanical pointing and gimballing errors that lead to a lower reliability than non-rotating antennas. Rotating radar systems are limited in their capability to adapt to changing target environments since scan patterns and rotation rates are often fixed. Also, it is impossible to achieve a track update rate higher than the search rotation rate, so tracking capabilities are greatly limited.

Phased Array Radar

Multifunction array radar (MFAR), also known as phased array radar and electronic scanning radar, presents some interesting capabilities and advantages over the radar systems discussed thus far. MFAR radars are composed of multiple identical radiators used simultaneously to create single or multiple independent beams. The radar beams are pointed electronically with control over both the azimuth and elevation directions, which allows for fixed orientation of the antenna array. The phase of each radiator is also controlled in order to create a single wavefront in the desired direction. A fixed, electronically steered system avoids many of the limitations incurred by the rotating radar systems. The phase and pointing of each element of the array is controlled individually. This allows for multiple functions to be performed simultaneously, with a certain number of array elements being dedicated to each desired function, which allows for a greater number of targets that can be tracked simultaneously.

Search and track are the two main functions that must be performed by any ballistic missile defense radar system. Phased array radar is able to perform both functions simultaneously and completely independent of each other. The amount of total radar resources dedicated to each function can be adjusted and adapted to best meet the requirements of any given situation and can be adapted almost instantaneously as the situation changes. The capability to control each radiator individually also allows for beamwidth control since the radiators assigned to each specific task can be spread across the surface of the array or all assigned from the same general area of the array. While a single parabolic dish radar is very limited in its scan pattern capabilities, rotation rates, and dwell times, a phased array radar presents many scan pattern alternatives. Elaborate scan patterns can be designed that can spend more overall time and have longer dwell times in certain areas of interest while limiting the search in areas less likely of contain a potential target.

Solution

After investigating the properties of the many different approaches to designing the missile defense radar, a phased array design was chosen. This choice was based on the many advantages that fixed, electronically steered multifunction radar possesses. The United States Department of Defense is basing our nation's missile defense program on fixed, phased array radar such as the Ballistic Missile Early Warning System (BMEWS) and PAVE PAWS (National Missile Defense). The United States currently operates five such radar. There are BMEWS sites at Thule Air Base, Greenland, Clear Air Station, Alaska, and Fylindales Royal Air Force Station, England. These sites were designed specifically to detect and track Intercontinental Ballistic Missile (ICBM) launches (BMEWS).

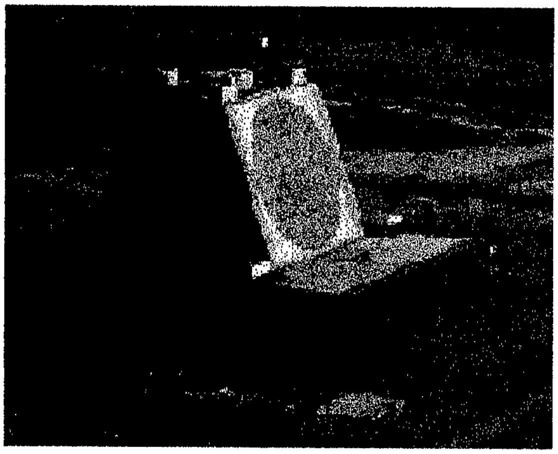

Figure 2. BMEWS at Fylingdales, England

PAVE PAWS radars located at Cape Cod AFS, Massachusetts and Bealle AFB, California are primarily used to detect Sea Launched Ballistic Missiles (SLBM) (PAVE PAWS). These radar sites are capable of obtaining very accurate data of the early stages of multiple SLBM and ICBM launches. The data received allow for early target discrimination, trajectory prediction, and early interceptor launch.

Both BMEWS and PAVE PAWS are very similar in their basic design. Since BMEWS is larger, more powerful, and designed for ICBM surveillance and tracking, BMEWS parameters and details were used for the base of the design. Each face of the BMEWS radar is about 32 meters high and 36 meters long (Fylingdales). By tilting each face back by 20°, targets can be detected from 3° to 85° in the elevation direction (Ballistic missile detection). Since each face has an effective 120° azimuth coverage, 3 faces are required for 360° coverage (PAVE PAWS). Each face is composed of 2,560 individual radiators with a peak power of 340 watts each (Fylingdales). This produces a maximum power output in excess of 2.5 megawatts. The average power output is 255 kilowatts (Skolnik 5.3). For search, BMEWS uses a frequency of 420-450 MHz and tracking, 1.215-1.4 gigahertz (Ballistic missile detection). The system is designed to detect and track objects with a radar cross section (RCS) of 10 square meters as far away as 5,000 kilometers (Ballistic missile detection).

IV. Radar Model

Modeling an electronically scanned phased array radar is very difficult. For the purposes of simulation, the radar was modeled as two independent, co-located parabolic radar antennas with half the antenna resources being dedicated to the search function and half to the track function. The model included characteristics such as near instantaneous beam pointing to the parabolic antennas to represent the capabilities of a phased array antenna.

Having the search and track radars located at the same site has one important disadvantage. By combining the returns from two separate radar sites, even if one were search quality and the other track quality, would be a very effective tool for reducing angular measurement error through triangulation. Having both the search and track radar at the same site, or only one phased array radar, adds no information to measurement accuracy calculations.

Search Function

S.A. Hovanessian in his Introduction to Sensor Systems provides the process of calculating the performance of both search and tracking radar. For a search radar, the signal to noise ration is calculated using the following equation:

$$\frac{S}{N}=\frac{P_{ave}A_e\sigma}{16R^4kT_eLL_a}\frac{t_a}{\Omega} \qquad (1)$$

S/N = signal to noise ratio
P_{ave} = average power
A_e = effective antenna area
σ = target RCS
R = range to target
k = Boltzman's constant
T_e = equivalent receiver noise temperature
L = antenna losses
L_a = atmospheric losses
t_s = scan time
Ω = scan volume in steradians (Hovanessian 14)

Effective area is found by multiplying the physical antenna area by an efficiency parameter η. The equivalent noise temperature is calculated by multiplying the antenna's characteristic noise figure by a standard temperature taken to be 290° K (Bogler 58). To obtain t_s, Ω is multiplied by the desired dwell time divided by the solid angle beamwidth. Beamwidth is equal to the wavelength divided by the antenna diameter. We used parameters from BMEWS, and then solved for range. Actual average power and antenna area was divided in half and a search volume of 20°x20° degrees was chosen. Figure 4.6 on page 4.22 of Rohan graphs clear day atmospheric losses per kilometer against frequency. Using a frequency of 435 MHz, the atmospheric loss was .0015 dB/km. This allowed for calculation of the overall losses due to atmospheric absorption for any given range assuming clear day conditions. Overall system losses were determined by adding typical non-atmospheric system losses (Rohan 94). Setting S/N to 10 dB, a typical detection requirement for search radar, unknown variables were set to typical values and then modified until the maximum detection range for a 10 m^2 RCS was about 5,000 km.

Once all of the variables were determined, we solved the equation for S/N with actual range as an input and then solved for the accuracy of the radar's measurements given the input range. At a range of 5,000 km, the following values were determined:

R = 5,000 km
P_{ave} = 435.2 kW
A_e = 155.94 m^2
σ = 10 m^2
$k = 1.38\times10^{-23}$ J/K
T_e = 800 K
L = 20
L_a = 5.62
t_s = 23.55 seconds
Ω = .122 steradians
S/N = 10.24 dB

Appendix A shows the calculations and final variable values for this range. Range accuracy is found using the equation:

$$\Delta R = \frac{c\tau}{4(S/N)^{1/2}} \tag{2}$$

where c is the speed of light and t is the pulse width (Hovanessian 104). BMEWS has a pulse width of 16 ms (Skolnik 5.8). Angular measurement accuracy is found using the equation:

$$\Delta\theta = \frac{.627\theta_{BW}}{(S/N)^{1/2}} \tag{3}$$

where θ_{BW} is the antenna beamwidth found by dividing the wavelength by the antenna diameter (Rohan 191). Velocity measurement accuracy is determined using the equation:

$$\Delta V = \frac{\lambda \Delta f}{4(S/N)^{1/2}} \tag{4}$$

where λ is the wavelength and Δf is the Doppler filter bandwidth (Hovanessian 104). A typical Doppler filter bandwidth is 1000 Hz (Skolnik 14.18). At a range of 5,000 km and on a clear day, the measurement accuracies are:

$\Delta R = 3.69\times10^{5}$ m
$\Delta\theta = 7.00\times10^{-3}$ radians
$\Delta V = 53.0$ m/s

Only the angular accuracy is used in the track radar performance calculations.

Track Function

The track function performance is calculated a bit different than that of the search function since there is no search volume that must be scanned. Since the tracking function is at a much higher frequency than the search function of the phased array radar, its beamwidth is much smaller. The search radar must have a fairly accurate angular measurement to feed to the track function in order for the tracking radar to find any potential targets. The tracking antenna gain is calculated using the equation:

$$G = \eta\left(\frac{\pi d}{\lambda}\right)^{2} e^{-2.76\left(\frac{\phi}{\phi_{3dB}}\right)^{2}} \qquad (5)$$

where η is the antenna efficiency, d is the antenna diameter, ϕ is the degrees the tracking bore site is from the target, and ϕ_{3dB} is the 3 dB beamwidth. The value of ϕ is determined by finding the magnitude of the search radar error, or the square root of the azimuth error squared plus the elevation error squared. Using the average angular error the search radar would provide to the track radar at 5,000 km, a gain of 44.4 dB is calculated using the following parameters:

η =.65
d = 19 m
ϕ = $4.95\text{x}10^{-3}$ radians
ϕ_{3dB} = $1.21\text{x}10^{-2}$ radians
G = $2.77\text{x}10^{4}$ = 44.4 dB

This Gain is used to calculate the tracking S/N using the equation:

$$\frac{S}{N}=\frac{P_{ave}G^2\lambda^2\sigma}{(4\pi)^3R^4kT_eLL_a} \tag{6}$$

S/N = signal to noise ratio
P_{ave} = average power
G = antenna gain
σ = target RCS
R = range to target
k = Boltzman's constant
T_e = equivalent receiver noise temperature
L = antenna losses
L_a = atmospheric losses (Hovanessian 15)

Atmospheric loss was determined to be .005 dB/km from Figure 4.6 on page 4.22 of Rohan for the tracking frequency of 1.3075 GHz. Atmospheric loss for the tracking frequency is considerably higher than that of the search frequency. Fortunately, the smaller beamwidth makes up for some of the lost S/N ratio. For tracking, the required S/N is also lower than for the search function, typically 3 dB (Hovanessian 16).

For the same distance on a clear day and the calculated gain, values for the variables and S/N ratio were determined to be:

$R = 5000$ km
$P_{ave} = 435.2$ kW
$G = 2.77\text{x}10^{4}$
$\sigma = 10\ m^{2}$
$k = 1.38\text{x}10^{-23}$ J/K
$T_e = 800$ K
$L = 20$
$L_a = 316.23$
$S/N = 3.06$ dB

Measurement accuracy is calculated for the same three parameters using the same equations as used for the search function. The accuracy results are:

$\Delta R = 8.43\text{x}10^{5}$ m
$\Delta\theta = 2.66\text{x}10^{-3}$ radians
$\Delta V = 40.3$ m/s

Appendix B shows all the final design parameters and calculations for the track function with the range set to 5,000 km.

V. The Simulation

For the computer simulation of our design project, a Minuteman III ICBM is being launched from Paris, France with the intended target being New York City. Originally the simulated radar site was placed at the BMEWS site in

Thule, Greenland. Unfortunately, this site is far to north and only had a couple minutes of view time of the missile as it flew along its trajectory. By moving the site to Daqortoq on the southern coast of Greenland, the radar could see the missile about 5 minutes after launch until interception. With the two S/N equations and all of the variables determined, the radar system was included in the Simulink computer model.

Search Function

The computer simulation will follow the following sequence. Initially, the radar system is dormant until cued by the battle manager with an azimuth and elevation pointing angle determined from data received from the space based IR sensors. The radar module will access the truth model data of latitude, longitude, and altitude in order to calculate the actual angles and range from the radar site to the missile. The search radar waits on the horizon if the detected missile is not yet in view. As soon as the missile enters the $20^\circ \times 20^\circ$ search volume, the S/N value will be calculated. After three successful signal returns are received above the set S/N threshold, azimuth and elevation with the calculated maximum angular measurement error is given to the tracking radar module. The search radar continues to follow the missile, and if necessary, provides updated target location to the track radar.

Track Function

The track radar also accesses the truth model and given the range and angular measurement error, calculates the gain and then the S/N of the radar return. From this information, the measurement accuracy will be calculated and the range, azimuth, and elevation angles will be given to the battle manager with error. The track radar continues to provide data to the battle manager as it tracks the missile until interception.

Limitations

There are currently several shortcoming and needs for improvement of the radar model. For example, the current detection process is based on binary detection theory. If the threshold S/N value is exceeded, there is an absolute detection. If not, there is no detection. The simulation does not account for false alarms or consider false alarm rates. The total radar resources of power and area that are allotted to the search and track functions are fixed and are not adaptable. This does not represent the capabilities of phased array radar very well. The gain equation does not take into account the projected aperture area to the target, always assuming the target is always located perpendicularly to the face of the antenna. This does not represent a fixed planar array adequately. To consider this a viable simulation of a phased array radar system, the shortcomings must be corrected.

Three additional improvements on the existing radar simulation would be to take potential adverse weather conditions into account, variation in measurement accuracy, and autonomous search capabilities. The atmospheric losses for both the search and track S/N equations are calculated based on clear weather conditions. A random variable should be added to add some variability in weather instead of always calculation the best case possible. On the other hand, the accuracy of the range, velocity, and angular measurements are always added as a worst case scenario. A randomly distributed variable should be added to the accuracies to better model measurement performance. Furthermore, since the search radar does not initiate its search until cued by the battle manager, if the IR detector fails to detect the missile, it will not be detected or intercepted. This does not represent the real world well since the search radars are constantly scanning the horizons, not relying solely upon IR satellite capabilities.

Discrimination of potential targets was another difficult task to simulate. The simulation included both a warhead and one decoy and the radar was to discriminate between the two. This is not an easy undertaking. Decoys are made so as to be indistinguishable from the real warhead. The only obvious method that the radar system would be able to distinguish the two would be if they had known, different radar cross sections. An enemy would do everything possible to make the decoy have the same RCS as the warhead, so using this method alone would be a very unreliable method of discrimination. None of the radar books that we reviewed even mentioned the topic. The decoy and warhead may have differing aerodynamic properties that may cause them to have differing trajectories, but this would be a time consuming and ineffective way of determining with any degree of reliability which was which. The safest and most effective way to approach the problem of potential decoys would be to treat all radar signal returns that appeared like a warhead as if they were a warhead, and react accordingly.

VI. Conclusion

Based on the radar system's performance requirements, the phased array is not only the best approach, but possibly the only approach to successfully meeting the demands of a system capable of ICBM defense and exoatmospheric interception by a ground based interceptor. Other radar systems do have advantages for other specific applications where phased array would not perform as well, but over all, phased array possesses the versatility required for an effective search and track radar.

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SEARCH

VARIABLE				EQUATION
Range =	R	5000000	m	
Frequency =	f	4.35E+08	Hz	
λ =	lambda	6.90E-01	m	c/f
Diameter =	D	19	m	
Average Power =	P	435200	W	
Antenna Efficiency =	eta	0.55		
Effective Area	Ae	155.94	m^2	eta*pi*(D/2)^2
Target radar cross section =σ =	sigma	10	m^2	
Search Volume	Az	20	deg	
	El	20	deg	
Solid search volume = Ω =	Omega	0.1218	steradians	Az*El/(57.3)^2
	to	0.20	sec	
	ts	23.55	sec	Omega/Bs*to
Boltzman's constant =	k	1.38E-23	J/K	
Effective Temperature =	T	800	K	
Loss =	L	20		
Athmospheric losses =	La	5.6234		
Beamwidth =	B	3.63E-02	rads	lambda/D
solid angle beamwidth =	Bs	1.03E-03	steradians	pi*(B/2)^2
Signal to Noise Ratio =	S/N	10.56	magnitude	(P*Ae*sigma*ts)/(16*k*T*L*La*R^4*Omega)
Signal to Noise Ratio =	S/N	10.24	dB	
Speed of light = c =	c	3.00E+08	m/s	
Pulse width =	tau	1.60E-02	ms	
Doppler Filter bandwidth =	DFbw	1.00E+03	Hz	
Range accuracy =	ΔR	3.69E+05	m	c*tau/(4*SQRT(S/N))
Angular measurement accuracy =	Δθ	7.00E-03	rads	0.627*B/SQRT(S/N)
Velocity measurement accuracy =	ΔV	5.30E+01	m/s	c/f*DFbw/4/SQRT(S/N)

TRACKING

	VARIABLE			EQUATION
Range =	R	5000000	m	
Frequency =	fr	1.31E+09	Hz	
λ =	lambda	2.29E-01	m	
Diameter =	D	19	m	
Pave =	Pave	4.35E+05	W	
Beamwidth =	B	1.21E-02	rads	lambda/D
eta =	eta	0.65		
Degrees off Boresight =	deg	2.84E-01	deg	from search function
		4.95E-03	rads	
Gain =	G	2.77E+04		eta*(pi*D/lambda)^2*e^(-2.76*(deg/(B*180/pi))^2)
σ =	RCS	10	m^2	
k =	k	1.38E-23	J/K	
T =	Te	800	K	
L =	L	20		
Athmospheric losses =	La	316.2278		
S/N =	S/N	2.02	mag	P*G^2*lambda^2*RCS/((4*pi)^3*R^4*Te*bc*L*La)
Signal to Noise Ratio =	S/N	3.06	dB	
Speed of light =	c	3.00E+08	m/s	
tau =	tau	1.60E-02	ms	
Doppler Filter bandwidth =	DFbw	1.00E+03	Hz	
Range accuracy =	ΔR	8.43E+05	m	c*tau/(4*SQRT(S/N))
Angular measurement accuracy =	$\Delta\theta$	2.66E-03	rads	0.627*B/SQRT(S/N)
Velocity measurement accuracy =	ΔV	4.03E+01	m/s	c/f*DFbw/4/SQRT(S/N)