

Jamming Efficacy of Variable Altitude GPS Jammer against Airborne GPS Receiver, Theoretical Study and Parametric Simulation

Ahmad Esmaelkhah¹, Niloofar Lavasani²

¹ Electrical Engineering Department, Engineering Faculty, Urmia University, Urmia, Iran

² Electrical Engineering Department, Engineering Faculty, Islamic Azad University, Shahr'e Quds, Iran

E-mail: a.esmaelkhah@urmia.ac.ir

Abstract

Satellite-based navigation systems, as one of the key infrastructure of development in manned and unmanned guidance systems, is vulnerable against the simplest form of attack in Electronic Warfare environments. This led us to investigate the described vulnerability of an airborne GPS receiver against jammers which are located at various altitude above the targeted point. To do that and to avoid encountering with unavailability of classified information about military-class missiles, some simplification was done and the problem was investigated in "Worst Case" conditions. Finally, the flight profile and radiation pattern of the antenna of the GPS receiver were theoretically modeled. Considering some assumptions, the other parameters were derived from them. At the end, a simulation software was developed and some results were extracted. The data was represented figuratively and the dependency of efficacy of jamming operation to the jammer's altitude and flight profile of the missile were discussed.

1. Introduction

Navigation, the art of finding the direction using predefined indications, have been evolved during the past century, especially after advent of long range wireless communication systems shortly before & during the WWII. The procedure of guiding & handing over a moving client, i.e. an aircraft, using fixed set of ground based RADARs was matured during the WWII [1], which are still in use. But the Achilles heel of these methods, was its dependency on existence of stable communication link between the reference points of navigation, i.e. TACAN¹ stations[2], and the moving client. Also there was another inherent problem in maritime applications. Long distances between the navigational point of reference and the offshore vessels beside the curvature of the Earth, makes the ships unreachable by signals of common RADAR systems. OTH radars² can be used, but their natural inability to locate the

client accurately and their structural and functional complexity, makes them non-functional for high speed applications, such as guiding cross-pacific airplanes.

During the 40s to 70s, some ground-based, long range navigational systems developed, mostly for maritime applications which some of them are still in use partially, mostly as backup navigation aids³[3, 4]. When the space-based communication systems were economically and technologically justified, the precursors were sent into the space, the TRANSIT⁴[5] And SECOR⁵[6]. Finally, the Global Navigation Satellite Systems, the GNSS(s), were designed and deployed, basically for military use, and are still under development[7]. Also some other verity of this system studied, developed and deployed by some private-sector organizations⁶[8], all of them are using triangulation method of navigation. But there were & there are concerns about intentionally or unintentionally jamming of these networks in various levels, from the control & monitoring to the positioning systems and subsystems [9]. Some counter-jamming, counter-spoofing and counter-deception methods developed specially for Global Positioning Systems, the American version of GNSS, the GPS. These methods beside the ability of accurate positioning make the GPS, and maybe the GLONASS, reliable enough for military applications.

The technological advancements are double-edged swords and parties of a military conflicts always tries to use this fact. One of the simplest form of Electronic Warfare is the Denial of Access [10]. As long as the input of a GPS receiver is saturated by unwanted signals with sufficient level of power, the positioning is impossible or at least unstable enough for stringent guidance of clients. This type of EW operation is not efficient but its infrastructural hardware is so simple to design and also very cheap to fabricate. Also more sophisticated and more expensive type of jammers, i.e. the Repeater Jammers or GPS deception systems, have to create a suitable level of jamming power at receiver's input. So the problem of effectiveness of a jamming can be reduced to investigation of Jamming to Signal Ratio, the JSR, at receiver' input [11].

¹ TACTical Air Navigation system

² Over The Horizon RADAR

³ Such as Decca (commissioned in 1942 & decommissioned in 2000~2001), LORAN or LONg Range Navigation system (commissioned in 1942 & some variant are still in use), OMEGA (commissioned in 1972 & decommissioned in 1997).

⁴ Also named as NAVSAT and Navy Navigation Satellite System (NNSS), commissioned in 1964

⁵ Abbreviation for Sequential Collation of Range, operational in 70s.

⁶ Such as Iridium Communication Satellite Constellation

The most important targets of these types of jamming, are costly Cruise Missiles and some other navigationally precise guided weapons or platforms, i.e. Unmanned Air Vehicles. As the inertial properties of a system can be used sufficiently to describe its mechanical behavior, i.e. its acceleration, velocity and location, most of these guided weapons and platforms are using Inertial Navigation System, the INS, as their primary mean of navigation. Some auxiliary tools, such as TERCOM⁷, DSMAC⁸ or Laser Altimeter, also have been used to correct the inherent integration offset of INS during longtime operation[12]. But the periodic use of GPS data is common, because of its precision & all-weather availability.

Despite of limitations on access the classified information about Cruise Missiles, the effect of variable altitude jammer on the GPS receiver onboard of a Cruise Missile were focused and investigated, using open-source and non-classified information. Finally, the question of “Is the Jammer at higher altitude is more effective?” was answered.

2. Materials and Methods

2.1. The “Worst Case” Method of Modeling

Unavailability of classified information, wide range of choices for GPS receiver and its accessories & different possible installation configuration of GPS receiver onboard of its carrier besides various possible jamming techniques and hardware, jammer installation and configuration, surrounding terrain and many other unknown or unattainable parameters caused the problem to be modeled in “Worst Case” conditions. So the principal & effective properties and parameters are chosen so that the “Real” conditions are practically more attainable and logically more reasonable. The results of final model will show the effect of our assumption in “Worst” reasonable case.

2.2. The Problem; Description and Simplification

The described problem can be reduced as a Line-of-Sight communication between jammer and GPS receiver. Because of the minor effect of atmospheric bending, refraction and absorption, sharp-edge diffraction & ducting at operating frequency of GPS receiver and engaged GPS Jammer, this assumption is logically and scientifically reasonable.

To discard the propagative effect of atmospheric phenomena, such as clouds, the conditions assumed to be as worst as possible for receiver. So the described communication link will be established in homogenous & isotropic transmission medium, i.e. the dry air.

To maintain the integrity of research, the gain of Jammer’s & GPS receiver’s antennas assumed to be different, i.e. G_j and G_r , respectively. Assuming the existence of stable communication link during the jamming operation, a tracking system is required to point the main lobe of jammer’s antenna toward the GPS receiver. To eliminate this requirement and its associated errors at this point, we

assumed the jammer’s antenna to be Omni-directional, a simple inherent tracking method in mobile communication systems.

To model in “Worst Case”, all of the performance-related parameters of the Jammer and the GPS receiver were assumed to be perfectly matched, ranging from the polarization of the antennas to its resonant frequency. While this assumption will let us to maximize the effectiveness of jamming operation, they are not so efficient in real applications and various kind of mismatches occurs. Some unknown but important and complex issues which must be modeled and simulated properly are:

- Flight profile: The way in which the GPS-receiver’s platform, i.e. the missile, approaches its target.
- Location of jammer: The position of the jammer in respect with targeted spot.
- Gain of receiver’s antenna & its orientation including the effect of missile’s structural complexity on it & its orientation during the fight.

Knowing these yet-unknown parameters finalizes the simulation of efficacy of jamming operation.

2.2.1. Flight Profile

As the Cruise Missiles are guidable & presumably programmable platforms, three types approaching procedure can be considered for various types of them. But to avoid loose of generality, the calculation will be done parametrically for an unknown flight profile which covers all of the mentioned scenarios.

Various types of targets make the manufacturer to develop various type of Cruise Missiles. For instance, ground-to-sea and sea-to-sea cruise missiles usually hits their target after fast increase in altitude and hitting them from above. Contrary to these family of missiles, some other air-to-ground and maybe ground-to-ground missiles hits their targets after a gentle decrease in their altitude, hitting from side or after a sharp decrease in their altitude hitting from above [12]. These methods of hitting targets, which named as the Direct Hit, the Overhead Hit and the Enhanced Overhead Hit, are illustrated in Figure 1.

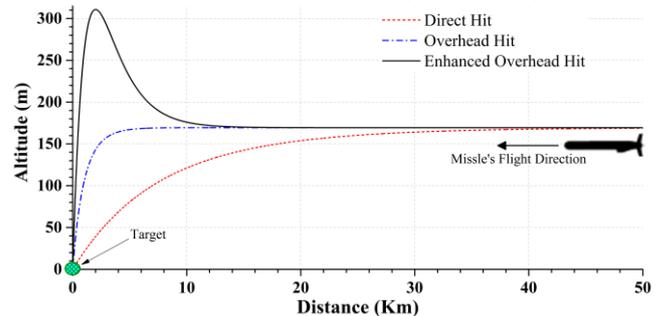


Figure 1. Different and possible scenarios hitting targets by cruise missiles.

There is a complicated issue which must be solved before modeling the flight profile to be started. In reality, the movement of airborne platform occurs in 3-Dimensional

⁷ Terrain Contour Matching

⁸ Digital Scene Matching Area Correlator

coordination system. To answer the question of “Is the need of 3-Dimensional calculation of results, a requirement?”, the reasons of that requirement are to be discussed. Some of them are:

- Non-symmetrical overall gain of receiver antenna (including all the coupling-effects from surrounding structures while it is installed on its position in the body of the missile) in respect with its perpendicular main axis.
- Inefficiency of interception effort to focus the main lobe of the Jammer’s antenna on moving platform during its approach procedure. These inefficiencies may be caused by the interception errors, weather condition, etc.
- Non-isotropic properties of transmission medium. For instance, the existence of fog, rain, different types of clouds, etc. along the flight profile.
- Non-isotropic properties of surroundings such as the Earth composition and its terrains.

To study the issue in “Worst Case”, we assume the last three of these causes are not applicable. So the interception method and system of interception have assumed to be completely efficient and precise. Also the properties of transmission medium discussed in 2.2 too (clear sky is assumed). The assumption of LoS Communication link vanishes the effect of surroundings.

Finally, without loose of generality, the overall gain of receiver antenna assumed to be symmetrical, but not isotropic, in respect with its perpendicular main axis. This assumption will cease the effect of structural complexity of Missile. So without loose of generality and “Worst Case” conditions, the problem has simplified into 2-Dimensional coordination system.

We need a general, or at least as general as possible, equation to model the described flight profiles. Obviously the final equation, as shown in (1), contains some adjustable parameter which will determine the type of flight profile.

$$h(x) = \sin \left(e^{\frac{-C_{DF}}{C_{PP}}} \right) \left(C_{MA} \left(1 - e^{\frac{-x}{C_{PP}}} \right) \right) + C_{CA} \left(1 - e^{\frac{-x}{C_{PP}}} \right) \quad (1)$$

Where C_{DF} is missile’s diving factor, C_{PP} is the variable parameter which controls the position of maximum altitude, C_{MA} controls the maximum altitude along the flight path & C_{CA} is altitude of missile at its cruise phase of flight. As long as the location of target assumed to be at $x=0$, equation (1) models all the three flight profile which illustrated in Figure 1. The tentative presented equation covers all the required properties of flight path if its variables to be adjusted properly.

2.2.2. Location of Jammer

To increase the intensity of jamming signal in surrounding areas around the target, which may extend for tens of kilometers, the GPS jammers are installed to operate in vicinity of the important targets, practically. Also the large

distance between the launch-site of the missile and the spotted targets, makes the small distance between the target and position of GPS jammer to be neglect-able. Due to these consideration, herein, we assume the GPS jammer exactly located in same position as the location of the target but at altitudes which can be higher than target’s altitude.

Assumed Omni-directional property of radiation pattern of the jammer’s antenna causes the 2-Dimensional calculation to be deployable.

The reader may note the effect of Earth, as a reflecting body, has neglected. But due to outstanding assumption of unity gain for Jammer antenna, the final gain of antenna in real configuration can be calculated using methods which were described in text books & the results can be replaced in simulation software.

The altitude of jamming system considered to be variable, ranging from ground-zero point to altitude as high as tens of thousands of meters [12]. The way in which the altitude of jamming system changes is not a matter of interest in our study. Also the operational parameters of the jammer are independent of the variation of its altitude.

2.2.3. The Gain of Receiver Antenna & Its Orientation

As documented, data extraction from at least 4 NAVSTAR satellites is required for triangulation to be done [7]. These satellites are moving at speeds as high as 14000 Km per hour and at altitudes as high as 22000 Km above the surface of the Earth. So these satellites are always crossing the observable sky, appearing and setting down periodically. If the location of observer assumed to be flat, he can detect eight to eleven NAVSTAR satellites at any arbitrary moment of time, which are moving in different direction in the sky. If this observer is equipped with a GPS receiver, it will analyze all the received signals and choose the most powerful and clear one as clocking reference and next three for triangulation purpose.

To receive more powerful signals from satellites and also to reduce the effect of reflections form surrounding terrains and buildings, the main lobe of GPS receiver antenna must be positioned upward, With almost constant gain over a reasonable angle around its main axis. The gain decreases as the angle of signal arrival direction nears $\pi/2$ or $-\pi/2$. The properties of structural composition of missile will eliminate the reception of signal at angles near π . As the Cruise missiles are dirigible platforms, they will not rotate along their longitude axis during the guided flight phase⁹. So the axis of main lobe of the GPS receiver’s antenna will always be perpendicular to the flight path, and is upward while the missile flying horizontally.

By advancement of phase array antenna and to reduce the effect of unwanted source of signals at same or adjacent frequency bands, some complicated algorithms and systems have been suggested [13], which uses this technique to track the satellites and to intercept their signals by lowering the

⁹ Some missile rotate after launch to orient their INS and some other navigational instruments, but after a while they will be sterilized and no rotation along its longitude axis will happen

gain of antenna in other directions. This type of systems usually require bigger antennas & are more complicated & expensive. These concept is out of interest of our study as detailed information about their actual performance & efficiency are not available and mostly are unreliable.

2.3. Mathematical Modeling

To calculate the efficacy of jamming operation against the airborne GPS receiver, choose of received jamming-signal's power level at receiver's antenna will not reduce the generality of study. This is due to the fact of Jamming-to-Signal Ratio¹⁰ is a very good parameter showing the performance of a receiver in electronic warfare environment. As the power of received C/A or P signals are not under control¹¹, the only variable and controllable parameter is the strength of jamming signal.

2.3.1. Modeling the Angle of Arrival¹²

Calculation of AoA for GPS receiver while receiving the jamming signal is essentially a milestone of this work. The assumption of virtual tracking of missile by jamming system, as describe in 2.2, has led to calculate the exact direction of received signal during the flight and at any arbitrary point of flight path. So the relationship between the AoA and the mathematically modeled flight path must be calculated and proved.

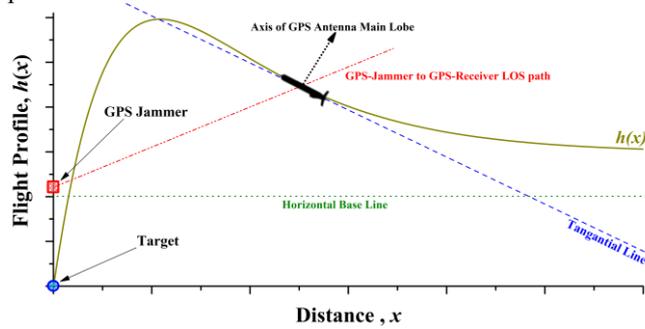


Figure 2. the figurative representation of simplified problem to calculate the normalized received power but the GPS receiver antenna onboard of missile

The altitude of jammer assumed to be h_{jammer} above target. it is simple to prove the AoA can be calculated as

$$AoA = \theta(x, h_{jammer}) = \frac{\pi}{2} - S(x) - H(x, h_{jammer}) \quad (2)$$

After some algebraic calculations, the final equation to calculate the AoA can be simplified as

$$S(x) = \tan^{-1} \left[\frac{-\frac{C_{DF}}{C_{PP}} e^{-\frac{C_{DF}x}{C_{PP}}} \cos \left(e^{-\frac{C_{DF}x}{C_{PP}}} \right) \left(C_{MA} \left(1 - e^{-\frac{x}{C_{PP}}} \right) \right) + \frac{C_{MA}}{C_{PP}} e^{-\frac{x}{C_{PP}}} \sin \left(e^{-\frac{C_{DF}x}{C_{PP}}} \right)}{\right]} \quad (3)$$

And

$$H(x, h_{jammer}) = \tan^{-1} \left[\frac{\frac{\sin \left(e^{-\frac{C_{DF}x}{C_{PP}}} \right) \left(C_{MA} \left(1 - e^{-\frac{x}{C_{PP}}} \right) \right)}{x}}{C_{CA} \left(1 - e^{-\frac{x}{C_{PP}}} \right) - h_{jammer} + \frac{h_{jammer}}{x}} \right] \quad (4)$$

The S , as the slope of $h(x)$, is a pure function of x and is independent of height of jammer. But the H , the Los distance, is dependent of x and h_{jammer} simultaneously.

2.3.2. Modeling the Antennas' Radiation Pattern

The radiation pattern of GPS receiver's antenna must be considered too. Ideally the actual and measured values must be places for calculation. But due to lack of detailed information about military-class GPS receivers and its accessories, the radiation pattern have been modeled too. Using this model will not reduce the generality of study as

- The measured data with suitable resolution can be uploaded to the final software.
- The presented model covers all the requirements such as antenna's main-lobe properties, side-lobe level properties and back-lobe modeling.

The model uses five adjustable parameters and can be simplified as

$$g(\theta) = \frac{|Sinc(C_{MLFZ}\theta)|}{g_{Max}} \left[\frac{C_{BLS} \left(e^{-|C_{ST}\theta - C_{SP}\pi|} + e^{-|C_{ST}\theta + C_{SP}\pi|} \right)}{+ C_{MLS} e^{-|C_{ST}\theta|}} \right] \quad (5)$$

Where the C_{MLFZ} ¹³ is proportional to the position of the first zero of the main-lobe of antenna, C_{BLS} ¹⁴ controls the size of the back-lobes, the C_{ST} & C_{SP} ¹⁵ are changing the position and size of side-lobes, C_{MLS} ¹⁶ is proportional to the size of the main-lobe and g_{Max} , the maximum size of radiation pattern, have been used to normalized the calculated radiation pattern. Figure 3 shows the various radiation pattern which are created by suggested model & the orientation of its flying platform. The model is capable of simulating wide verity of radiation patterns, ranging from almost Omni-directional to high gain one.

¹⁰ will be abbreviated as JSR, as seen in various documents.
¹¹ The next generation of NAVSTAR satellites will use phase arrayed antennas to control the coverage area and also the received power level in desired areas up to %20 of its nominal values [7].

¹² Will be abbreviated as AoA.
¹³ Main Lobe First Zero
¹⁴ Back Lobe Size
¹⁵ Side Lobe Position & Side Lobe Translation
¹⁶ Mail Lobe Size

As the described, in simplified problem, the missile flies to its target directly in 2-dimensional coordination system. This is why only one of E-plane or H-plane radiation patterns have been used. For 3-dimensional calculations, use of both is this patterns are essential, which is out of interest of this work.

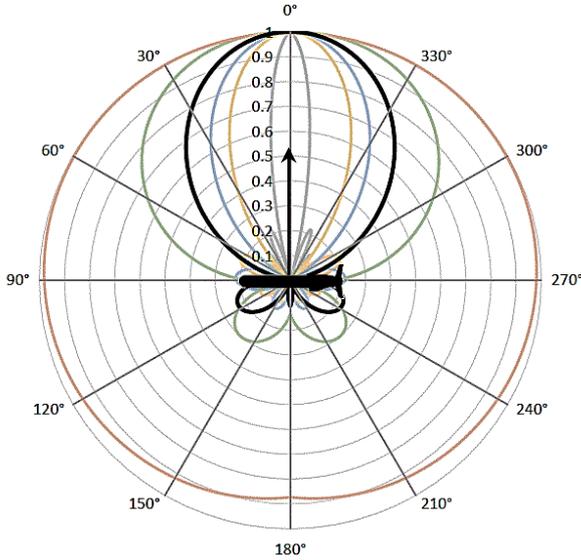


Figure 3. Various radiation patterns of the GPS receiver antenna onboard of missile

2.3.3. Modeling the Final Normalized Received Power

Friis equation which is governing the received power by the receiver's antenna, the P_R , can be calculated as

$$P_R = \frac{c^2}{(4\pi f)^2} \left(\frac{P_J G_J G_R}{R^2} \right) \quad (6)$$

Where c is the speed of light in ms^{-1} , f is the frequency of propagated electromagnetic wave in Hz , P_J is the radiated power of jammer in *Watt*, G_J is the gain of jammer's antenna which assumed to be 1, G_R is the gain of GPS receiver's antenna ($G_R = g(AoA) = g(\theta)$) & R is the LoS distance between the jammer and the missile in meters.

As the transmission frequency and radiated power are constant during the jamming operation, these parameters will be considered as constant values. Also the LoS distance between the jammer and missile is a function of $h(x)$ and h_{jammer} . So equation (6) can be simplified as

$$P_R(x, \theta, h_{jammer}) = k \left(\frac{g(\theta)}{x^2 + (h(x) - h_{jammer})^2} \right) \quad (7)$$

Where

$$k = \frac{c^2 P_J}{(4\pi f)^2}; k \in \mathfrak{R} \quad (8)$$

As k is a real and constant coefficient, it has no considerable effect in our calculation and we can assume it as unity for simplicity, without loss of generality. Also the θ is AoA of received signal; So (7) can be rearranged as

$$P_R(x, h_{jammer}) = \left(\frac{g\left(\frac{\pi}{2} - S(x) - H(x, h_{jammer})\right)}{x^2 + (h(x) - h_{jammer})^2} \right) \quad (9)$$

Hence, in Worst Case, the received power of the GPS receiver's antenna from jammer transmitter is mostly under influence of distance of missiles from targeted point & the altitude of jammer.

2.4. Simulation

To deploy the model numerically, to check its validity & to see if it is applicable or not, a GUI-based simulator has developed in MATLAB R2013a. The simulator uses adjustable controls for various parameters of flight-path, radiation pattern of GPS receiver's antenna and the height of GPS Jammer. Finally, four essentially important curves can be plotted. As Figure 8 illustrates, these curves are:

- Flight path: the altitude profile of the cruise missile (in meters) during its flight as a function of distance (in kilometers)
- Normalized radiation pattern of the GPS receiver's antenna: the polar curve of the radiation pattern has been plotted with 90 degrees of clockwise rotation with one degree of resolution.
- AoA: the angle-of-arrival of jammer's signal (in degrees) as a function of distance (in kilometers)
- Normalized flight profile vs. normalized received power from GPS jammer.

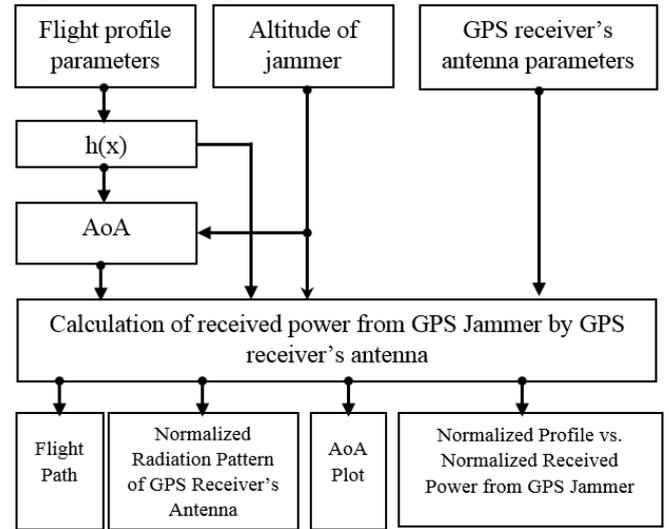


Figure 8. The Overall block diagram of the developed simulation software

The interpretation of these four plots will be discussed later in detail. Without introducing any limitation, the maximum distance of missile from targeted point & the resolution of calculations have been adjusted to 50km & 100m respectively.

3. Results & Findings

To investigate the results, we need to generate them by introduction of some EW and scenarios. There is an essentially important condition which must be obeyed; each scenario will be tested twice, once while the jammer is a ground-based transmitter & once with an airborne jammer at predefined altitude. The scenarios are

1. Direct Hit attack (DH)
2. Over-Head Hit attack (OH)
3. Enhanced Over-Head Hit Attack (EOH)

Table. 1 listed the parameters of (1) to generate these scenarios. The flight path of these scenarios are shown in Figure 2.

Table 1. The values of four adjustment parameters of flight profile of the missile.

Scenario	C _{DF}	C _{PP}	C _{MA}	C _{CA}
DH	1.06	18.1329	50	297.838
OH	1.06	1.25268	50	297.838
EOH	1.06	1.25268	1915.63	297.838

In Direct-Hit scenario, the missile mostly launched by an airborne platform, e.g. a bomber aircraft, and decreases its altitude gradually [12]. On the other hand, in Over-Head Hit and enhanced version of it, the missile will start its final phase of maneuvers in last few kilometers of its flight [12]. So the selected values to adjust the flight paths are reasonable.

Table 2 listed the parameters of radiation pattern of GPS receiver's antenna. Also Figure 3 illustrates the selected radiation pattern of GPS receiver's antenna by bolded black line curve.

Table 2. Selected value of adjustment parameters of (5) to generate the suitable radiation pattern for GPS receiver

C _{MLFZ}	C _{MLS}	C _{BLS}	C _{ST}	C _{SP}
0.708461	28.8462	67.3808	0.028845	2.65721

Use of patch antennas in GPS receivers, low altitude flight of Cruise Missiles during their cruise phase of flight, effect of metallic components beneath the installation position of GPS receiver inside the missile's body & abatement of receiving the reflected GPS signals from Earth or surrounding terrains are the main reasons to justify the selected values, listed in Table 2. The HPBW of the selected radiation pattern is approximately 162°, symmetrically ~81° around the main axis. Also it represents two alike side-lobes, approximately -6.5 dB below the maximum achievable gain. A back-lobe of -10 dB below described maxima exists too.

As the variability of jammer's altitude is a key feature of this work, the angle-of-arrival of jammer's signal has been calculated and figuratively illustrated in Figure 4. Due to stronger jamming signal & start of procedures to approach the target in its vicinity, the last 20Km missile's path toward the target has more interesting features.

As the AoA of jamming signal for various scenarios have been calculated, the normalized received power from

jammer by the GPS receiver's antenna can be calculated too. Figure 5 illustrates results of this calculation for various scenarios, separately, and for jammers with different altitudes of 0, 800m and 4300m. the red dashed line on Figure 5 represents the minimum "Effective Jamming Power Level" and considered to be -13dB of the maximum attainable value.

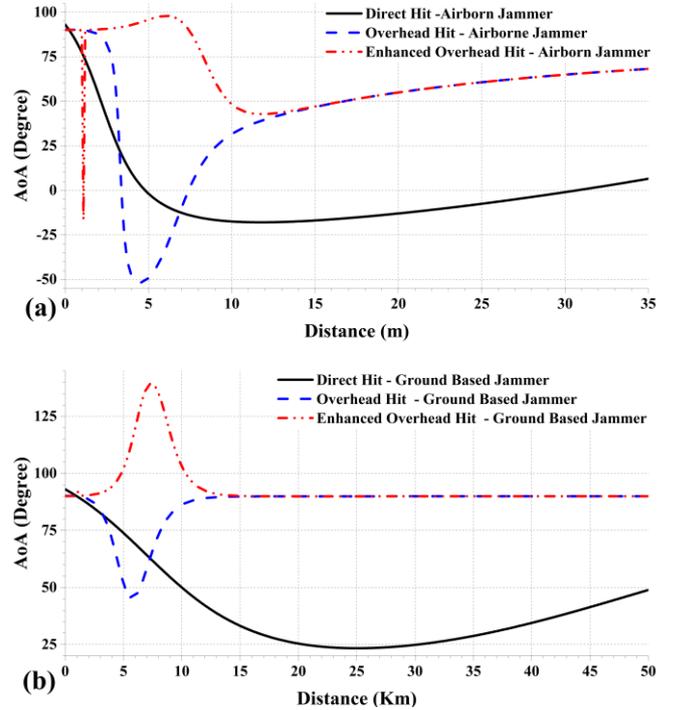


Figure 4. The Angle of Arrival (AoA) of the jamming signal for a) air-born GPS jammer, b) ground-based GPS jammer

4. Discussion

4.1. Efficacy of EW operation

In reality, the efficacy of electronic warfare operation(s) against the positioning capabilities of guided weapons depends on many factors. As we focused on one of the secondary positioning systems of a cruise missile, the onboard GPS receiver, the power level of received jamming signal is a key factor to estimate the efficacy. So higher power of received jamming signal will increase the probability of successful jamming operation. But as the cruise missile's navigational platform mostly uses of various methods, we will not & we cannot decide what will happen then. It highly depends on type of cruise missile and its algorithms for navigation & its subsystems.

The AoA of jammer's signal at GPS receiver's antenna have been illustrated in Figure 4 for different scenarios and jammer at various altitudes. As seen, each pair of curves, i.e. the OH for airborne and ground based jammer, are showing similar behavior but with different rates and scales. The final received power depends simultaneously to the AoA & the radiation pattern of the receiver's antenna. Each scenario covers three separate situations in which the GPS jammer's altitude is one of the 0, 0.8 & 4.3 Km above the ground zero. As seen in all of scenarios, the normalized received power for $h_{jammer}=0$ and $h_{jammer}=0.8$ Km is nearly identical. So use of

GPS jammer at low altitudes for simulated flight profiles and radiation pattern of GPS receiver's antenna is not efficient & will not change the efficacy of EW operation impressively.

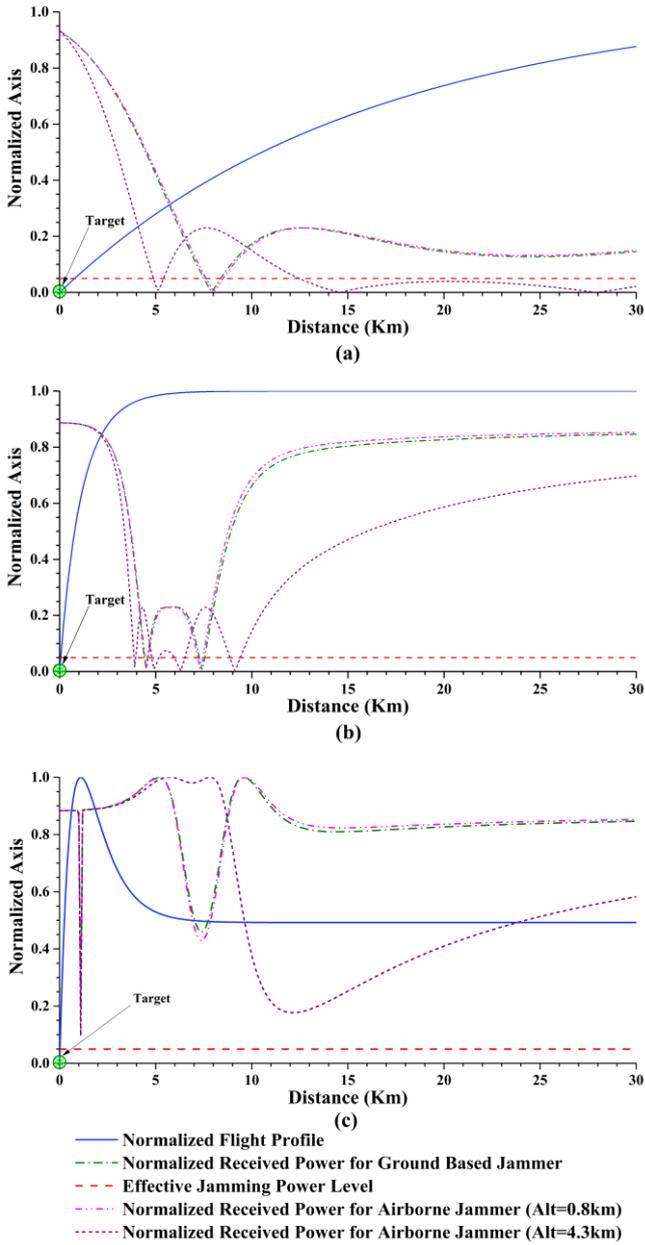


Figure 5. Various scenarios of approach a) Direct Hit, b) Over-Head Hit, c) Enhanced Over-Head Hit

Finally, to investigate the operational behavior of GPS receiver while is not saturated by jamming signal, the Reinstatement Time, or T_R , have been defined as duration in which the GPS receiver is not effected by the jammer's signal. As seen in Figure 6, in OH scenario, the missile at distances of about 3.92Km and 5Km away of targeted spot, is not jammed. For a conventional cruise missile at 550 mph (245.872m/s) of speed [12], the T_R can be calculated as 508 & 1423 milliseconds for 125m and 360m gaps, respectively. As the GPS receiver starts to locate its platform in Hot Start mode, both of these values seems to be sufficient for it to extract its current position again. This means the missile

corrects its navigational offsets ~ 3.9 Km away of targeted point & will hit it after 15.86 seconds. This fails the EW operation and the missile will hit the targeted spot using its offset-eliminated INS.

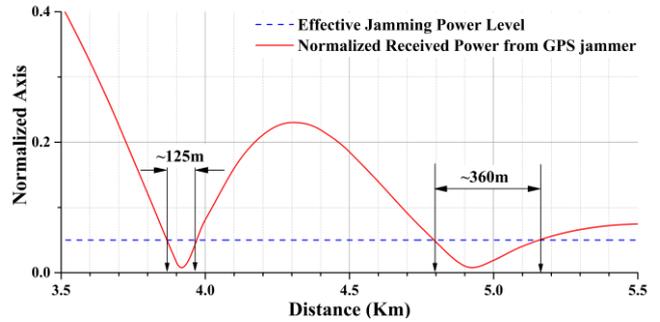


Figure 6. the Reinstatement Time of incoming missile with OH scenario of approach.

As the T_R and its associated concluded results are highly dependent of the type of cruise missile and also the technical performance of installed GPS receiver, detailed discussion about the results requires detailed information about. it is very useful to calculate and investigate the issue while the detailed information is available.

4.1.1. Direct Hit (DH) scenario

Direct Hit, as the simplest form of attack against usually fixed targets, is the most vulnerable scenario in EW environment. As seen in Figure 5(a), the slow rate of change of AoA caused considerable T_R for ground based and low altitude jammers. For high altitude jamming, the GPS receiver on board of missile is not jammed from 30 to ~ 12 kilometers away of target and another T_R can be measured too. As increase of jammer's altitude nears the nearest T_R , use of low altitude jammer seems to be more efficient.

4.1.2. Over-head Hit (OH) Scenario

The interesting feature of rapid dive to the spotted target, caused the OH scenario to be more complicated for jamming. During its route to the target, the missile and its onboard GPS receiver experience various levels of power from jamming source. But there are multiple points, between 10 to 4 Kilometers from target, in which the received power is below the Effective Jamming Power Level. The associated Reinstatement Time at these points are long enough for GPS receiver to locate the missile precisely. As the altitude of GPS jammer increases, the position of these points drifts away of target, but is neglect-able. Figure 5(b) illustrates the issue.

4.1.3. Enhanced Over-Head Hit (EOH) Scenario

While the missile flies along an EOH profile, as seen in Figure 5(c), there are no measurable Reinstatement Time in last 20Km of flight. The received power level is almost identical for ground based, low and high altitude jammers in last 6Km, but promising decrement of received power level from high altitude jammer shows the EW operation could be successful for jammer(s) located at lower altitudes. Also there is a sharp decrease at $x=1$, caused by the local extrema. If happens, the

associated Reinstatement Time at this point seems to be too short for GPS receiver's correlator(s) to extract the location, even while it works on Hot Start mode.

Table 3. The Summarized results of jamming operation against missiles at various scenarios

		Attack Scenarios		
		Direct Hit	Over-head Hit	Enhanced Over-head Hit
Type of Jammer	Ground Based	Effective	Effective	More Effective
	Low Altitude	Effective	Effective	More Effective
	High Altitude	Less Effective	Effective	More Effective

5. Conclusion

The problem of efficacy of jamming against an airborne GPS receiver has simplified logically and physically. To prevent loss of generality & to increase its applicability, the Cruise Missiles are chosen as the flying platform. As the detailed information about these missiles are classified & unavailable, the flight profile and the radiation pattern of the GPS receiver's antenna have modeled. Also to ensure the validity of results, the problem studied in "Worst Case" conditions. The Direct Hit (DH), Over-head Hit (OH) and Enhanced Over-Head Hit (EOH) scenarios have chosen to investigate the effect of ground based, low altitude and high altitude jammers. As listed in Table 3, the EOH is the most vulnerable scenarios and will be jammed effectively. But the other 2 scenarios has the key advantage of measurable long Reinstatement Time(s).

Acknowledgements

We would like to thank Dr. M. Zare & Dr. M. Mahdavi of Islamic Azad University of Shahr-e Qods for their continuous support and motivations.

References

[1] A. GULYÁS, British radar in WWII, *Hungarian Defense Forces*, 34. *Special Operations Forces Battalion, Szolnok, Hungary*, Vol. 7, No. 1 (2008) 175–185, Available at: www.zmne.hu/aarms/docs/Volume7/Issue1/pdf/14guly.pdf

[2] W.L. Garfield, TACAN: a navigation system for aircraft, *Proceedings of the IEE - Part B: Radio and Electronic Engineering*, Volume: 105, Issue: 9, March 1958, DOI: 10.1049/pi-b-1.1958.0045

[3] J.A. Pierce, An Introduction to Loran, *The Proceedings of the IRE and Waves and Electrons*.34, May. 1946. 216-234

[4] P. B. Morris; R. R. Gupta, R. S. Warren, P. M. Creamer, Omega Navigation System Course Book. Volume 2, Technical rept. Mar 1990-Jul 1994, *Analytic Sciences Corp Prading, MA*

[5] L. Pisacane The Legacy of Transit: Guest Editor's Introduction by Vincent L. Pisacane, *Johns Hopkins APL Technical Digest*, Vol 19, Number 1, 1998.

[6] J. H. REID, The SECOR Approach to Coordinate Determination for Ships and Aircraft, Navigation, *Journal of Institute of navigation*, Volume 11, Issue 4, Winter 1964, 393–416

[7] L. Eldredge, GNSS Program Status, *Satellite Navigation Summit*, March 10, 2010, Munich, Germany.

[8] M, Joerger, L. Gratton, B. Pervan, Analysis of Iridium-Augmented GPS for Floating Carrier Phase Positioning, *NAVIGATION: Journal of The Institute of Navigation*, Vol. 57, No. 2, Summer 2010, 138-160.

[9] M. Lichtman, J. D. Poston, S. Amuru, et al., A Communications Jamming Taxonomy, *IEEE Security & Privacy*, Volume: 14, Issue: 1, Jan.-Feb. 2016, 47-54, DOI: 10.1109/MSP.2016.13.

[10] D. Adamy, EW 102: A Second Course in Electronic Warfare, *Artech House*, 2004, 117-119, ISBN-13: 978-1580536868.

[11] S. Hicks, Advanced Cruise Missile guidance system description, *Proceedings of the IEEE National Aerospace and Electronics Conference*, 24-28 May 1993. *NAECON*, Dayton, OH, USA, DOI: 10.1109/NAECON.1993.290941

[12] Carlo Kopp, Tomahawk Cruise Missile Variants, BGM/RGM/ AGM109, Tomahawk/ TASM /TLAM/ GCLM/MRASM, *Technical Report APA-TR-2005-0702*, April, 2012, Available at: <http://www.ousairpower.net/Tomahawk-Subtypes.html>

[13] U. S. Kim, D. Akos, F. Bastide, Simulation and Validation of a GPS Antenna Array Concept for JPALS Application, *ION GPS/GNSS 2003*, 9-12 September 2003, Portland, OR, 1852-1860.