THAAD: What It Can and Can't Do

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North Korea's recent nuclear test and satellite launch have provoked a strong response from the United States, the Republic of Korea and the international community. One result has been a greater willingness on the part of South Korea to undertake negotiations with the United States on deploying the Terminal High-Altitude Area Defense (THAAD) system on the peninsula to protect it from North Korean ballistic missile attacks. Adding THAAD to missile-defense deployments that already include Patriot systems would likely substantially enhance South Korea's capacity to minimize the damage caused by a large North Korean missile attack. However, it is important to note that a layered defense will not be able to completely block such an attack. As a result, missiles armed with nuclear weapons could cause significant casualties as well as damage in the South.

The North Korean Ballistic Missile Threat

Pyongyang possesses a substantial arsenal of short- and medium-range mobile ballistic missiles deployed throughout the country, including: 1) 500 Hwasong-5 (Scud-B), and Hwasong-6 (Scud-C) missiles with a range of 300-500 km; and 2) 200 Nodong systems with a range of 1,000 km. Each of these systems is capable of carrying nuclear as well as chemical and biological warheads, though most are fitted with conventional explosives warheads. Their primary role, other than those armed with nuclear weapons, would appear to be to disrupt or slow operations at airbases, military garrisons and port facilities, all critical to the defense of South Korea, given plans to flow outside forces onto the peninsula in case of a war.

The DPRK also has a small stockpile of about 100 KN-02 (Soviet-era SS-21 Tochka) missiles with a maximum range of between 90 and 120 km. Unlike the Scud-based missiles, the KN-02 is accurate enough to attack specific point targets, such as radars, command headquarters or critical infrastructure with consistency. It also appears to be capable of carrying a range of different warheads.

Pyongyang has showcased two longer-range ballistic missiles: the intermediate-range Musudan—which appears to be a modified version of the Soviet-era, submarine-launched ballistic missile, the R-27 (SS-N-6)—and the KN-08 intercontinental ballistic missile (ICBM). Neither has been test flown and the maturity of the designs and development process is unknown. High-end projections forecast that North Korea could field roughly 24 of each missile by 2020, though performance reliability would be questionable without a full set of flight trials. Lastly, North Korea is actively developing a submarine-launched ballistic missile, though testing to date has been largely unsuccessful, as one might expect in the preliminary phases of a program.

Ballistic Missile Defense in South Korea

To defend against the North Korean missile force, South Korea currently has a mix of Patriot systems with the older PAC-2 batteries to be upgraded or replaced by the more modern PAC-3 by the end of the year. These are supplemented by US deployments of the same weapon. The PAC-3 system is intended to provide protection for key installations such as airfields, ports, critical infrastructure, military command centers or leadership locations. Comprised of Extended Range Interceptors (ERINT), an MPQ-53 phased-array radar, launch canisters, a mast group for communications, and a fire-control unit, PAC-3 intercepts short- and medium-range missiles by colliding with the threatening missile or warhead at low-altitudes (less than 25 km, or endoatmospheric) and at short distances (35-40 km or less) from its location. Because PAC-3 destroys targets at low altitudes, it is said to be a 'lower-tier' defense system.

The THAAD system intercepts incoming short, medium and intermediate range ballistic missiles above the atmosphere—exoatmospheric intercept—providing an upper-tier layer of defense when operating in conjunction with the lower-tier Patriots. THAAD consists of five primary components: interceptor missiles, launch canisters, AN/TPY-2 phased array radar, a fire-control unit, and support equipment—including a power-generation and cooling units. These can detect and track targets at a range of about 1000 km—assuming the target has a radar-cross section of about 1 m^2.

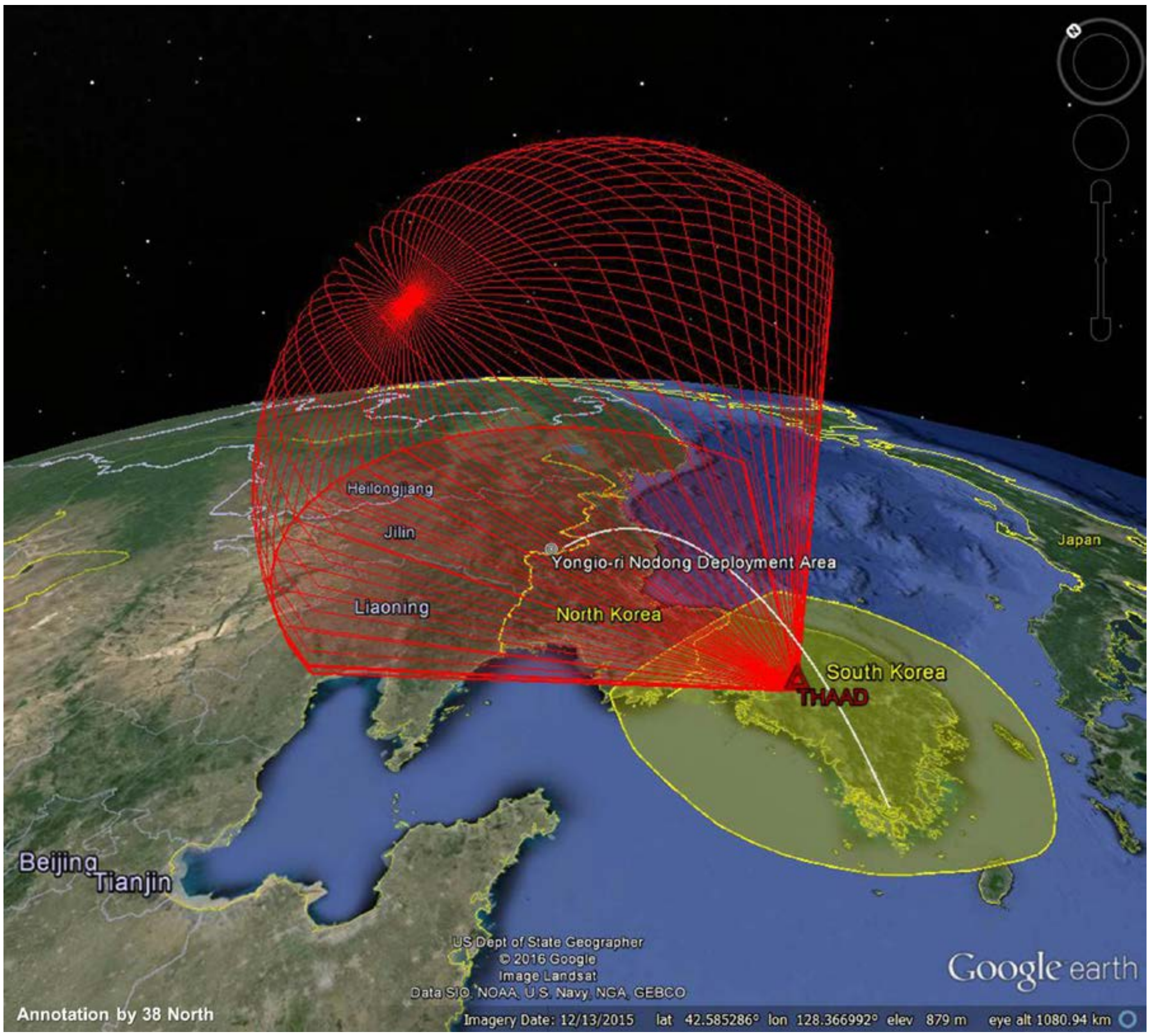
Two Illustrative Layered Defense Deployments

The first scenario for deployment of a layered defense assumes that North Korea launches its missiles from an operating area in the far north near its border with China. A single THAAD battery is stationed at an airbase a few kilometers north of Cheongju, which, in principle, will be able to defend a major portion of South Korea except a few islands south of the peninsula.[1] This conclusion assumes that North Korean missiles fly on what is called a minimum-energy trajectory: a normal flight path that maximizes range for a specified burn-out velocity. However,

[1] One measure of missile defense performance is the expanse of territory a system can protect, often called the "defended footprint." An estimated footprint can be calculated if the locations of the defense system and attacking missile launch sites are known, the speed and trajectory of the target are defined, and the defense's radar characteristics and its interceptor acceleration and burn-out velocities are known.

analysis shows that if North Korea were to alter the launch trajectory—for example using a depressed or flattened trajectory—that would shift the footprint to the south by up to 90-100 km. As a result, that might create gaps in coverage and, as a result, the South may need to deploy a second THAAD battery. Depressed and normal, minimum-energy trajectories differ in the same way a line drive and fly ball take different paths to the outfield in baseball.

Figure 1. Radar coverage of THAAD.



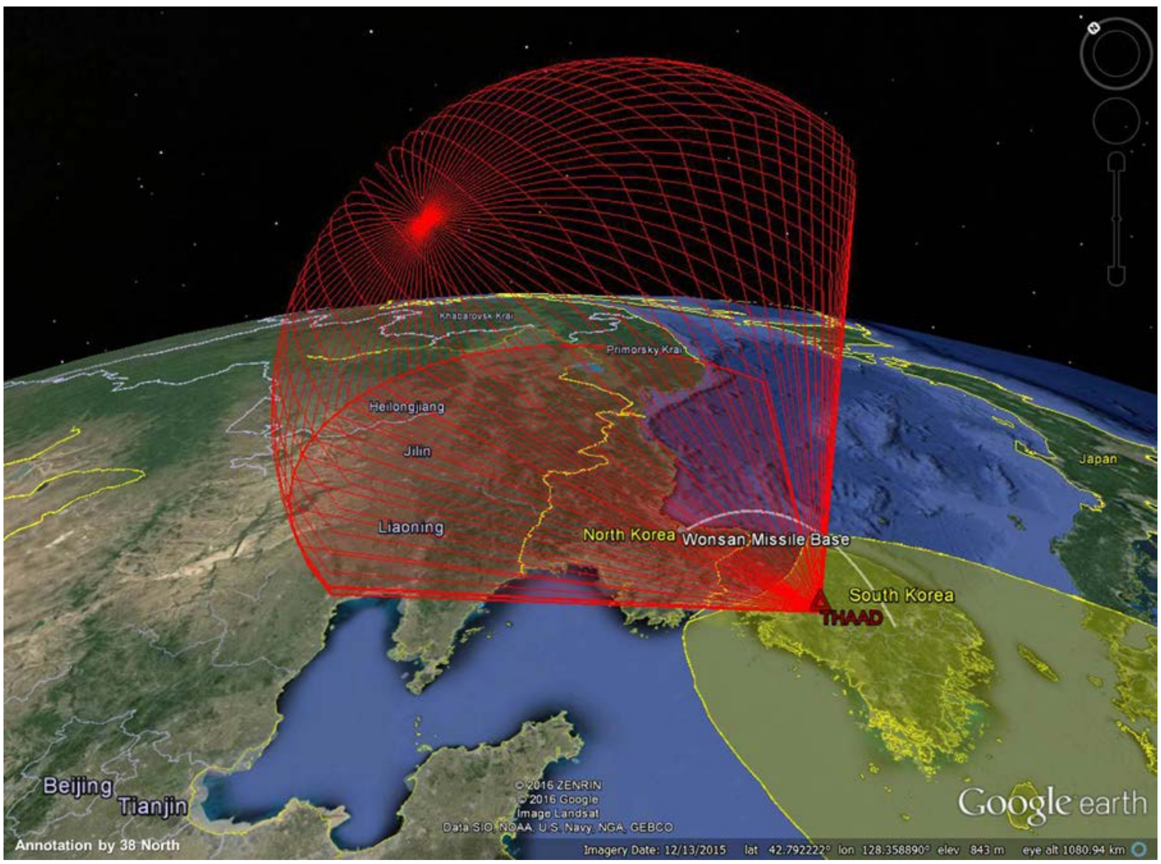
The radar coverage for the THAAD's AN/TPY-2 radar is shown in red, the defended footprint in yellow, and a single Nodong trajectory in white. The defended footprint is estimated by calculating the boundaries assuming the Nodong is on a minimum-energy trajectory. The footprint is defined as the kinematic limits of the THAAD system in this scenario; the actual footprint will be slightly smaller.

Figure 2 assumes that North Korea launches missiles from much farther south, from a base near Wonsan, just north of the demilitarized zone. Given this launch position, covering the entire territory of South Korea under varying North Korean launch positions, missile trajectories and missile types, will require two batteries. A single battery still provides coverage of most of South

Korea, except for the northeastern corridor. The shape of the footprint is different primarily because the interceptor and Hwasong launch locations are near enough to each other to allow THAAD to intercept in the North Korean missile's ascent phase, in addition to the terminal phase of flight. THAAD's ability to intercept short-range missiles in the ascent phase has yet to be demonstrated, so prudence dictates that a second THAAD battery located near the south end of the peninsula would be required to ensure short-range missiles launched by North Korea from positions within 100 km of the DMZ can be engaged successfully.

All told, this preliminary analysis of THAAD capabilities indicates that two THAAD batteries are required to defend all of South Korea.

Figure 2. Kinematic limits for THAAD's defended footprint.



The kinematic limits for THAAD's defended footprint for Hwasong and Nodong missiles launched from a base near Wonsan is shown on yellow.

Layered Defenses and Interceptor Efficiency

While two THAAD batteries can be deployed in such a way to cover all of South Korea, an additional critical question is how effective will the system be in destroying incoming missiles. Because THAAD intercepts targets at altitudes above 50 km and is capable of protecting large areas, it ideally complements the lower-tier PAC-3, which protects point targets. In essence, intercepting targets at multiple levels, or tiers, offers more opportunities to succeed and improves intercept efficiency, which is the calculated number of interceptors needed to achieve a specified measure of protection. Interceptor efficiency is governed primarily by the probability an individual interceptor will collide with and destroy a missile or warhead. It is often referred to as the "single-shot probability of kill," or SSPk. Historically, missile-defense designers at the US Missile Defense Agency have sought to achieve SSPk values of between 0.8 and 0.9, which means a single interceptor should succeed 80 to 90 percent of the time. Recent development and validation testing of THAAD indicate a kill probability of 0.8 is feasible, though design goals and test results may not be replicated under wartime conditions. Nonetheless, assuming an SSPk of 0.8 offers a measuring stick for evaluating the theoretical benefits of deploying THAAD in South Korea.

It is unclear what performance criteria South Korea or the US military have established for missile defenses on the peninsula. Two criteria are posited here for purely illustrative purposes. The first criterion would require the missile defense architecture to intercept all attacking threats with a probability of 0.75, and the other would dictate a probability of 0.9 that no attacking missiles leak through the defenses. The latter criterion might be required as an absolute minimum if North Korea is launching nuclear-armed missiles; the former, more relaxed criterion, might be acceptable for conventionally-armed attacks.

If one further assumes that two interceptors are launched at each layer of defense, the SSPk requirement to meet the overall defense criterion that all warheads in an attack are destroyed with a probability of 0.75, or a more stringent probability of 0.90, can be calculated. For illustrative purposes, assume the attacks consist of either 20 or 50 missiles at a time, which is a small fraction (less that 10 percent) of the overall stockpile held by North Korea, but is reasonably consistent with the estimated number of trained and equipped firing brigades capable of launching Hwasong and Nodong missiles under wartime conditions.[2] The benefits of layering

[2] The total number mobile launchers (transporter-erector-launchers or TELs) is not the limiting factor here. Rather, road-mobile missile operations are supported by a large logistics trail, including trucks for carrying the oxidizer and fuel, pumping trucks to transfer the propellants to the missile, surveying units to establish an accurate determination of location and missile alignment prior to launch, weather units to measure wind speed at various altitudes, repair and maintenance teams, trailers to carry spare missiles, cranes to transfer missiles to the TEL, command and control trucks and teams, security and protection teams. The overall logistics requirement involves tens of vehicles and hundreds of trained personnel.

the defenses are captured in Table 1, where the calculated results for one- and two-tiered defenses are presented.

Table 1. Benefits of layering defenses.

	Probability of No Leakage P(0) = 0.75		Probability of No Leakage P(0) = 0.90	
Warheads in Attack	20	50	20	50
One Layer	SSPk = 0.881	SSPk = 0.924	SSPk = 0.928	SSPk = 0.954
Two Layers	SSPk = 0.654	SSPk = 0.725	SSPk = 0.731	SSPk = 0.786

The Single Shot Probability of Kill (SSPk) requirement for individual interceptors is calculated for each scenario. For example, if the attack contains 50 warheads, and the overall defense criterion is that no warheads leak through a two- layer defense with a probability of 0.75, the SSPk requirement is 0.725. Two interceptors are allocated to each warhead at each layer of defense.

The results captured in Table 2 illustrate the conclusion that a layered defense is likely to be more effective. In a single-layer defense where two interceptors are fired at each of the 20 or 50 attacking warheads, the requirement that all warheads are destroyed 75 or 90 percent of the time cannot be satisfied unless the SSPk of each interceptor is significantly greater than 0.80. If two layers are operational when an attack of 20 or 50 warheads is executed, the SSPk requirement is less than 0.8. This suggests that if THAAD and PAC-3 can achieve the same degree of success on the battlefield as in validation testing to date, a two-tiered defense in South Korea can meet the notional requirements assumed here.

In addition to reducing the SSPk value needed to defend against 20 or 50 missiles, a layered defense can also reduce the total number of interceptors that must be fired, assuming the first intercept attempt occurs early enough to facilitate a "shoot-assess-shoot" strategy. Shoot-assess-shoot is possible if the upper-tier (THAAD) intercept attempt occurs early enough in the threat missile's trajectory to allow the lower-tier defense (PAC-3) to determine if the THAAD succeeded before launching the PAC-3 interceptors. For each success by THAAD, the PAC-3 defense would not have to fire its interceptors, thereby preserving them for use against future attacks. This becomes increasingly important as North Korea increases the number of missile firings above the 20 or 50 launches assumed.

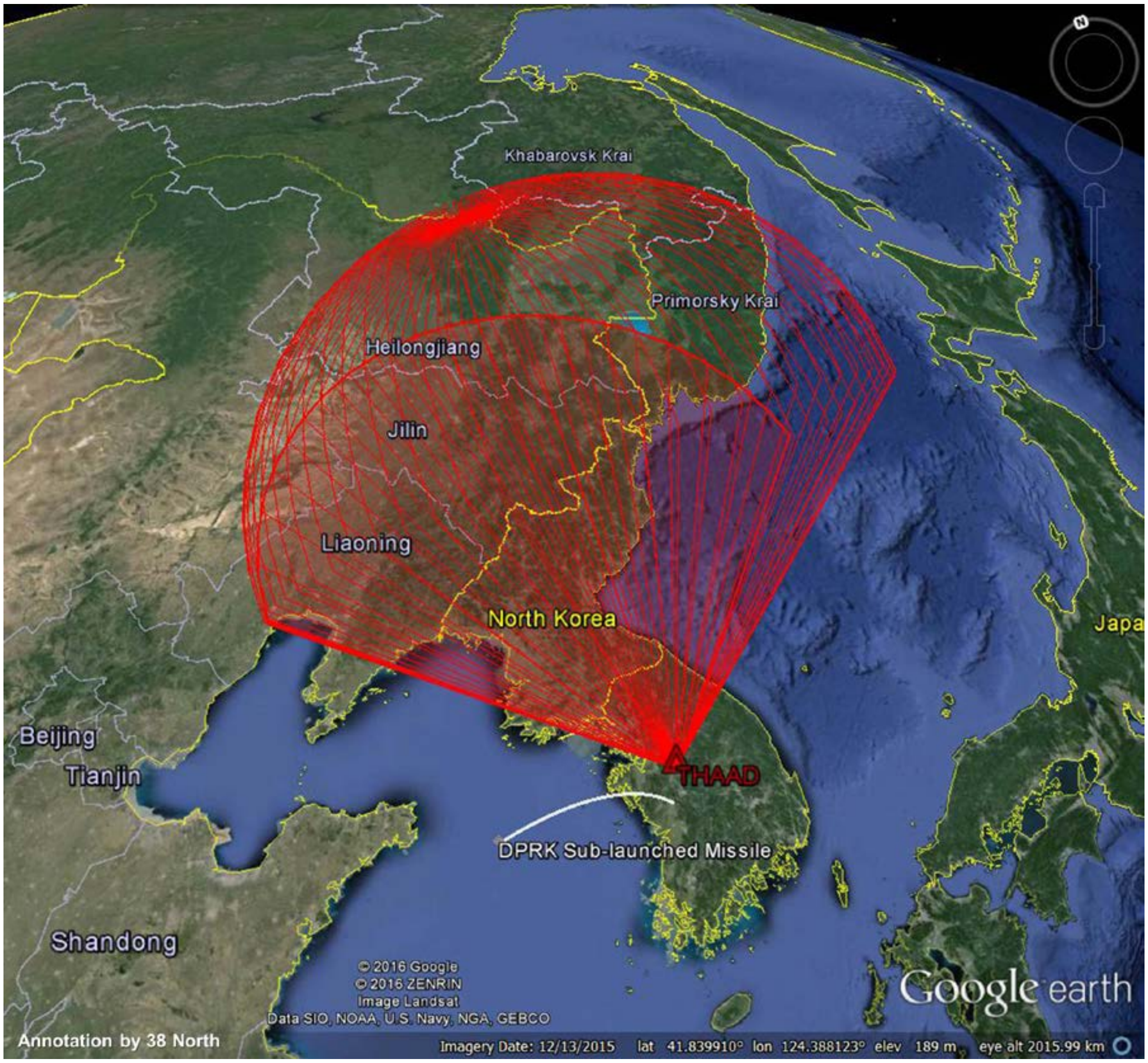
Also, if each of the PAC-3 batteries has access to THAAD radar data, it would be possible for them to be launched before the target enters PAC-3 radar coverage. This scenario is referred to as a "launch on remote," where one system launches its missiles on data generated by a remote sensor. PAC-3 batteries with a launch on remote capability would, in principle, have the capacity to protect a larger swath of territory, in some limited cases nearly doubling its defended footprint.

Some Significant Caveats

While THAAD can provide an important additional capability to protect for South Korea, a critical question is whether Pyongyang's large missile inventory will afford it opportunities to overwhelm the postulated one-to-two THAAD battery architecture. A single THAAD battery holds a limited number of ready-to-launch interceptors, likely ranging from 48 to 96. Spare interceptors can be stockpiled, though at great expense. This implies that one THAAD battery can defend against 20 and 50 attacking missiles if two interceptors are assigned to each incoming warhead. If additional interceptors are available, the launch canisters can be reloaded within an hour or so. However, there is no assurance that North Korea would pause firing its missiles to allow THAAD to reload. And given that North Korea has hundreds of Hwasong and Nodong missiles, one can easily recognize how large the defenses would have to be if the mission was to attempt intercepts on all incoming missiles over an extended time. Further, the AN/TPY-2 fire-control radar is limited in terms of the number of objects it can track while also providing updated guidance information to the interceptors in flight. Once again, if North Korea launches more than roughly 20 missiles simultaneously, this would likely saturate the radar, as it would necessarily be tracking 60 objects at once. The precise limitations are classified, though it is clear that if the objective is to blunt large salvos from North Korea, at least two or more THAAD batteries would be required.

Lastly, to protect against missile attacks launched from North Korean territory, all of the PAC-3 and THAAD radars would necessarily be pointed north. If North Korea successfully develops and deploys a submarine-launch ballistic missile, as it has been attempting over the past year or two, the missile defenses discussed above would be ineffective against the missiles fired from the waters east, west and south of the lower Korean peninsula.

Figure 3. Limitations of THAAD radars.



A North Korean ballistic missile launched from a submarine off the South Korean coastline would not be detected by missile defense radars pointed north to detect, acquire and track missiles fired from North Korean territory. The THAAD's three-dimensional radar envelope is shown in red, the submarine-launched missile trajectory is shown in white.

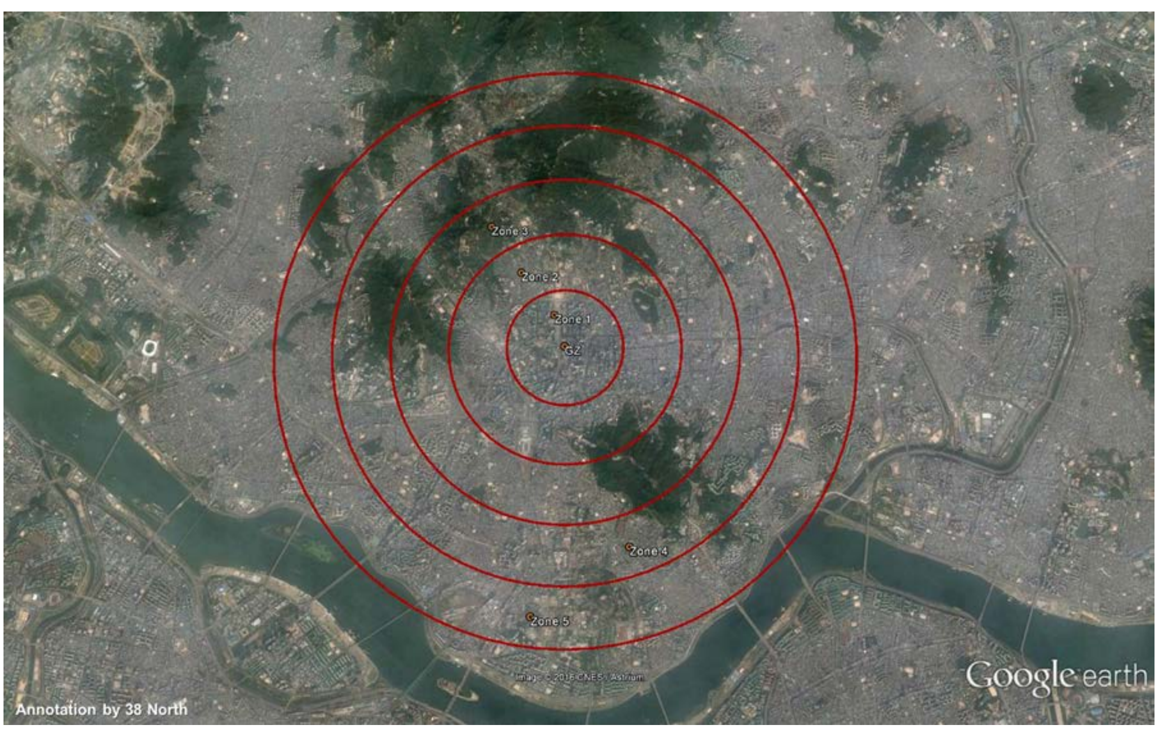
The Nuclear Option

No missile defense system or architecture will be "leak proof." Rather, missile defenses are designed to reduce the number of missiles striking critical targets, much in the way air defenses retard attacks by an enemy's air forces. If North Korea fires conventionally-armed missiles, a low leakage rate is acceptable since the damage caused will be manageable. However, missiles equipped with nuclear warheads are another matter entirely. Even if only one penetrates the defenses the death and damage would be immense. In this context, the addition of THAAD, or any other missile-defense system will not guarantee that South Korea is immune to Pyongyang's nuclear-armed missiles.

To better understand to catastrophic damage caused by a nuclear bomb, let's assume that one missile with a nuclear warhead beats THAAD and lands on Seoul. A 20 kiloton warhead would result in casualties extending up to 5 km. from the point of detonation. The data in the following table shows the casualties in each of the five rings/zones shown in the Google Earth satellite image below plus the total casualties in comparison with the total population of Seoul proper.

Figure 4a-b. Estimated casualties per zone from one nuclear-armed missile.

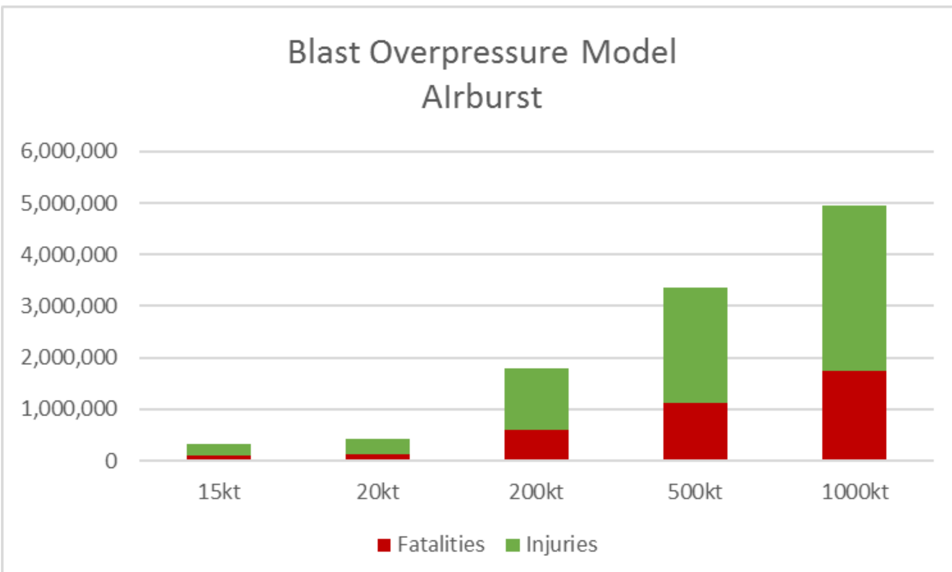
20 kt Airburst				
Ring/Zone	**km from GZ**	**Fatalities**	**Injuries**	**Total**
1	1 km	46,885	4,743	51,628
2	2 km	63,281	62,061	125,342
3	3 km	20,868	105,152	126,020
4	4 km	0	87,265	87,265
5	5 km	0	29,269	29,269
		131,034	288,491	419,525
	% of Pop.	1.25%	2.76%	4.02%



The following are estimates for casualties from different weapon yields ranging from 15kt to 1000kt (1mt) using the same model.

Figure 5a-b. Estimated casualties per different weapon yields.

Overpressure Model, Airburst Detonation				
Weapon Yield	**Fatalities**	**Injuries**	**Total**	**% of Population (Seoul)**
15kt	110,843	225,345	336,189	3.22%
20kt	131,034	288,491	419,525	4.02%
200kt	595,682	1,204,914	1,800,595	17.24%
500kt	1,127,947	2,236,652	3,364,598	32.22%
1000kt	1,751,136	3,213,095	4,964,230	47.54%



Conclusion

The deployment of one or two THAAD batteries in South Korea would substantially enhance its capacity to defend against a North Korean missile attack. To be sure, there is no perfect defense against ballistic missile attacks, but the probability of greatly reducing the damage resulting from missiles with conventional warheads increases when THAAD is incorporated into the defense architecture. When viewed through the lens of providing maximum protection from a North Korean missile threat, accepting the American offer to provide THAAD to the Republic of Korea is a prudent and defensible policy decision for Seoul.

However, the added defensive capability will have to be weighed against other considerations. Chinese objections to the deployment of THAAD (an assessment of whether those objections are rebased on a realistic assessment of the system is beyond the scope of this article) are clear. The economics of missile defense must also be considered. It is considerably more expensive to deploy and operate THAAD to South Korea, than it will be for North Korea to grow the size of its arsenal or to quickly invest in additional missiles, missile launchers and trained crews in order to overwhelm the defenses. Last, as this analysis shows, any system designed to destroy incoming missiles will have leakage. If those missiles are armed with nuclear weapons, that leakage could have catastrophic results.

Officials in Seoul will have some difficult decisions ahead of them, but the analyses here should partially refute arguments that say THAAD will not significantly benefit South Korea when countering the short-range, Hwasong missile threat from North Korea in the immediate future.

Note on Methodology

There are many variables in calculating projected population casualties due to the effects of nuclear weapons. The causes of population fatalities and injury from nuclear weapons fall into two categories: prompt effects and fallout. Prompt effects include exposure to ionizing radiation (photons and neutrons), blast overpressure and thermal (skin burns, eye damage). Prompt effects occur immediately after a nuclear weapon is detonated. Fallout effects include long-term exposure to radioactive particles falling from the atmosphere downwind from a nuclear detonation.

The yield of nuclear weapons is based on estimates of current capabilities or projections of future capabilities. Cities are considered "soft" targets. Nuclear weapons allocated to "soft" targets are calibrated to detonate at optimal height (air burst) to produce the most damage. Air burst weapons produce negligible fallout which was the case for both Hiroshima and Nagasaki. If a nuclear weapon was ground burst or burst low enough where the fireball touches the ground then fallout would occur requiring more extensive calculations including variables for weather, wind direction and speed, fallout exposure time (hours, days, weeks, months), radioactive decay, and long term population sheltering.

Population and population density are known variables. The population density is the average density over the city's entire area. The actual population density varies throughout a city. In Hiroshima, the population density near ground zero was far higher than the rest of the city. Related factors are the day of week and time of day when the detonation would occur. Population densities in downtown business areas are far higher during normal weekday work hours then they are at night or on the weekends. If the population was given sufficient warning of an impending attack, evacuations could occur, thus reducing the size of the population exposed. Various shelter protection factors that can reduce the effects of a nuclear detonation are based on the type of shelter such as is underground, frame house, multi-story upper or lower floors, concrete structures of various thickness, and vehicles (autos, trucks, buses). Sheltering can mitigate both prompt and fallouts effects.

Mathematical models are used to estimate the casualties from nuclear explosions. These models attempt to predict the probability of deaths and injuries from the effects of nuclear explosions. Mathematical models are created from extrapolations of information in the Hiroshima data archive, available in publications such as Glasstone & Dolan's, "The Effect of Nuclear Weapons" [1]. Scaling the yield of the Hiroshima weapon for peak blast overpressure and distance allows simulations with weapon yields larger than that of Hiroshima. Many computer programs have been created that use the mathematical models to provide rapid simulation for a large number of scenarios with a full range of weapon yields and dozens of input variables for both prompt and fallout effects. Some of these programs are available in the public domain [2]. The results of these simulations can vary significantly depending on the scope and range of input variables and the sophistication of the computer models.

Traditionally the standard method for determining casualties is based on extrapolation of peak blast overpressure distances from Hiroshima data for airburst detonations—the “overpressure” model. There are other more elaborate models, one of which is the conflagration model (firestorm effects) whereby the casualties are increased because the population surviving the initial blast does not escape the firestorms found near the outer damage rings/zones [3]. The following are the results of simulating a single 20kt nuclear warhead airburst at optimal height over Seoul, South Korea using the traditional “overpressure” model based on data from both Glasstone & Dolan [1] and Von Hippel, et al. [3]. Seoul proper:

Population	10,442,426
Land Area Sq. Km.	605.25
Density People/Sq. Km.	17,253
Radius of City km	13.88

As noted previously, alternate input variables and alternate simulation models will result in a wide range of results. However, it is clear from the results of the simulations above that even a single Hiroshima/Nagasaki-like nuclear detonation (20kt) will cause significant casualties.

References:

[1] US Department of Defense and the Energy Research and Development Administration, *The Effects of Nuclear Weapons*, by Samuel Glasstone and Philip J. Dolan, (Washington, DC, 1977), http://nnsa.energy.gov/sites/default/files/nnsa/inlinefiles/glasstone%20and%20dolan%201977.pdf. Includes a “Nuclear Bomb Effects Computer” circular slide rule.

[2] “HotSpot – Health Physics Codes for the PC,” Lawrence Livermore National Laboratory, https://narac.llnl.gov/hotspot; and Alex Wellerstine, “NUKEMAP,” The College of Arts and Letters, Stevens Institute of Technology, 2012-2014, http://nuclearsecrecy.com/nukemap/.

[3] William Daugherty, Barbara Levi and Frank von Hippel, “Casualties Due to the Blast, Heat, and Radioactive Fallout from Various Hypothetical Attacks on the United States,” Center for Energy and Environmental Studies, Princeton University (Report #PU/CEES 198, 1986).