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Long-range Nuclear Cruise Missiles and Stability

George N. Lewis[a] and Theodore A. Postol[b]

Long-range nuclear-armed cruise missiles are highly accurate and are capable of reaching most targets within the United States and the Commonwealth of Independent States (CIS) from launch points beyond their borders. Neither the United States nor the CIS has air surveillance systems capable of providing reliable warning against cruise missiles. Thus it is possible that a small-scale cruise missile attack could go entirely undetected until the nuclear weapons arrived over their targets. Such an attack could destroy the other country's entire strategic bomber force on the ground and severely damage its strategic command and control system, perhaps to the point of endangering the ability of its ICBM force to be launched on warning. This capability makes long-range nuclear cruise missiles potentially one of the most destabilizing of all nuclear weapons.

INTRODUCTION

Long-range nuclear-armed cruise missiles* are widely perceived as stabilizing additions to the US and CIS nuclear arsenals. This perception arises primarily from their relatively low speed, which is viewed as making them unsuitable for use in a first-strike nuclear attack. However, this simple characterization neglects more troubling aspects of these weapons. Cruise missiles are already the most accurate of all strategic nuclear missiles. More

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a. Defense and Arms Control Studies Program, Massachusetts Institute of Technology, Cambridge MA 02139
b. Defense and Arms Control Studies Program and Program in Science, Technology, and Society, Massachusetts Institute of Technology, Cambridge MA 02139

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* We will generally omit the words "long-range nuclear-armed" from in front of "cruise missiles." Unless otherwise stated, all subsequent references to cruise missiles should be understood to mean long-range nuclear-armed cruise missiles.

important, neither the United States nor the CIS has air surveillance systems capable of reliably detecting cruise missiles. This raises the possibility that cruise missiles could be used in a zero-warning nuclear attack. Viewed from this perspective, cruise missiles may be among the most destabilizing of all nuclear weapons.

Despite the end of the Cold War, both the United States and the CIS continue to maintain large strategic nuclear arsenals, key parts of which are ultimately dependent on tactical warning for their survivability. Systems for providing such warning take many years to construct, and efforts to improvise warning capabilities if relations deteriorate or if a crisis arises could result in dangerous false alarms. As long as both countries continue to rely on strategic nuclear forces that are dependent on warning for survivability they should not neglect the health of their warning capabilities.

This paper considers the threat to stability posed by cruise missiles. It begins with a discussion of relevant technical characteristics of cruise missiles. Next we assess the capabilities of the US air surveillance system and conclude that it is not capable of providing reliable warning of small-scale cruise missile attacks.* Given these warning deficiencies, the ways cruise missiles might be used in zero-warning nuclear surprise attacks are discussed and the resulting threat to stability is assessed. Possible responses to the threat to stability posed by cruise missiles will be considered in a subsequent paper.[1]

CRUISE MISSILE CHARACTERISTICS

So far only the United States and the CIS have deployed long-range cruise missiles[2] (these deployments are summarized in table 1). All of these air-launched cruise missiles (ALCMs) and sea-launched cruise missiles (SLCMs) are nuclear armed and intended for land-attack missions, except for the US Tomahawk, which also has land- and ship-attack variants with conventional warheads, and a number of US ALCM-Bs which have been converted into conventional land-attack missiles.[3] In addition, except for the not yet deployed

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* Because of a lack of information on CIS systems, the technical analyses in this paper will focus on US systems.

Table 1: Long-range nuclear cruise missiles[a]

Missile	Type	Range (km)	IOC[b]	Number[c]
		US		
ALCM-B	ALCM	2,500	1981	1,715
Tomahawk	SLCM	2,500	1984	337
ACM	ALCM	3,800–4,500?[d]	1991	-
		CIS		
AS-15	ALCM	3,000	1984	hundreds
SS-N-21	SLCM	3,000	1988	100?
AS-X-19	ALCM	3,000?	?	-
SS-NX-24	SLCM	3,000?	?	-

a. The INF treaty resulted in the elimination of three types of US or Soviet long-range ground-launched cruise missiles (respectively similar to the Tomahawk SLCM, the SS-N-21, and SS-NX-24) that were either under development or had been deployed.

b. IOC is initial operational capability.

c. All long-range nuclear SLCMs have been withdrawn from ships and placed in storage as a result of the Bush and Gorbachev arms initiatives of September and October 1991.

d. The range of the ACM is from Thomas K. Longstreth and Richard A. Scribner, "Verification of Limits on Air-launched Cruise Missiles," in Frank von Hippel and Roald Z. Sagdeev, eds., *Reversing the Arms Race: How To Achieve and Verify Deep Reductions in the Nuclear Arsenals* (New York: Gordon and Breach, 1990), pp.181–235.

Soviet high-flying supersonic AS-X-19 and SS-NX-24, all these missiles are designed for subsonic, low-altitude flight. The US SLCMs have been deployed both on surface ships and attack submarines; so far the CIS SS-N-21 has been deployed only on attack submarines.[4] President Bush's nuclear arms initiative of 27 September 1991 and the response by then President Gorbachev have resulted in the withdrawal of all nuclear SLCMs to on-shore storage sites, although these weapons "would be available if necessary in a future crisis."[5]

The characteristics of cruise missiles which must determine their capability to attack targets deep within the United States or the CIS are their range, guidance, and radar cross section. We discuss each of these in turn.

Table 2: Estimated maximum straight-line ranges (in kilometers) for several speeds and at several constant altitudes for a nuclear Tomahawk cruise missile[a]

		Altitude *kilometers*	
	Sea level	**3.05 kilometers**	**6.10 kilometers**
V = Mach 0.55	3,330	3,890	4,000
V = Mach 0.65	3,020	3,860	4,490
V = Mach 0.75	2,650	3,580	4,550
$V = V_{best}$[b]	3,400	3,920	4,600

a. Some insight into the variations of range with speed and altitude shown in this table can be gained by looking at figure 3 of appendix A, which shows the optimum missile speed (for best range) as a function of altitude and missile fuel weight. For example, figure A-3 of appendix A shows that the optimum speed at sea level varies between about Mach number $M = 0.45$ and $M = 0.61$. Thus if the missile is constrained to fly at a constant speed, $M = 0.55$ will give a greater range than either $M = 0.65$ or 0.75. At an altitude of 6.1 kilometers, however, $M = 0.75$ will give the best range, as over most of the missile flight the optimum speed is above $M = 0.7$.

b. The ranges in the line "$V = V_{best}$" are calculated using an optimized speed that varies with the missile weight.

Range

Table 1 lists the official US figures for the ranges of US and CIS cruise missiles: 2,500 kilometers for the US ALCM-B and Tomahawk and 3,000 kilometers for the CIS AS-15 and SS-N-21.[6] However, at least for the US missiles, this figure is an "operational" range that takes into account factors such as maneuvers around defended areas, course deviations to overfly predesignated terrain in order to update inertial guidance systems, vertical maneuvers to avoid obstacles, reserve fuel requirements, flight at higher than optimal speeds through defended areas, and low-altitude flight.[7] Thus, the extent to which these range figures represent either the relative or absolute range capabilities of these missiles is unclear.

We have constructed a simple model of the flight characteristics of the Tomahawk cruise missile and have used this to estimate its range under various flight conditions. Some results are listed in table 2 (the calculations and assumptions underlying these estimates are described in appendix A). Table 2 lists straight-line ranges* at three altitudes for three constant speeds and for

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* By "straight-line range" we mean the distance flown along a great-circle path without any course deviations or altitude changes.

an optimized speed that varies as the missile's fuel is consumed.[8]

A reasonable assumption in determining operational range is that the entire flight will be flown at low altitude. This suggests that the 3,400 kilometer estimate in table 2 is the relevant straight-line range. To obtain the stated operational range, this must then be reduced by about 26 percent.[9] The lesson of table 2 is that the range of a cruise missile is strongly dependent on its mission flight profile. The 2,500 kilometer operational range of the nuclear Tomahawk does not mean that it cannot strike targets at ranges of 3,000 or 3,500 kilometers; conversely, if the 3,000 kilometer range of the CIS cruise missiles is actually a maximum range, this does not necessarily imply that they could strike a target at a range of 2,500 kilometers under all operational conditions.

In order to illustrate the significance of such ranges, figures 1 and 2 show the coverage of the United States and the CIS that can be provided by sea-launched SLCMs with an operational range of 3,000 kilometers. As figure 1 illustrates, essentially the entire United States could be covered by cruise missiles launched from two or three submarines. It is often argued that the United States is more vulnerable to SLCMs than the CIS because a far greater proportion of its assets are located near coasts. However, while this may be true for short-range cruise missiles, figure 2 illustrates that most of the CIS is also vulnerable given current US cruise missile ranges. Indeed, even before the breakup of the Soviet Union, the CIS may have been considerably more vulnerable, given the US lead in long-range SLCM deployments and US advantages in submarine and antisubmarine warfare technologies. A similar situation holds for ALCMs, where CIS bombers must fly over or near US allies in order to reach the United States.

Substantial increases in cruise missile range appear to be possible (see appendix A). Without increasing missile volume, which will often be constrained by factors such as launcher dimensions, range increases of up to 50 percent for a Tomahawk-like cruise missile appear feasible, and increases of a factor of two may ultimately be possible. Such increases in range would allow the launch of cruise missiles from much greater standoff ranges.[10] This is particularly significant since, at present, the best hope of detecting a cruise missile attack may be the detection of the launch platform or the actual missile launch.

Figure 1: Coverage of the US by 3,000 kilometer range SLCMs.

Guidance

The US Tomahawk and ALCM-B navigate using an inertial guidance system assisted by a terrain contour matching (TERCOM) system.[11] This allows them to achieve a virtually range-independent accuracy of 60–80 meters or less, comparable to or better than any other strategic weapon.[12] Together with their 5 to 150 kiloton variable-yield W80 warheads, this accuracy is sufficient to destroy even highly hardened targets.[13]

The TERCOM system requires that cruise missiles overfly areas that have

Figure 2: Coverage of the CIS by 3,000 kilometer range SLCMs.

been previously mapped. In addition, since these missiles do not have a forward-looking terrain avoidance system, low-altitude flight must be made over carefully presurveyed paths. This approach to guidance hinders operational flexibility and makes mission planning a painstaking and time consuming task.[14] On the other hand, it allows these missiles to fly extremely low[15] and to maneuver around areas of known defenses, thereby making them much more difficult to detect and intercept. It is believed that the CIS AS-15 and SS-N-21 cruise missiles employ a similar guidance mechanism. The guidance mechanism used by the US Advanced Cruise Missile (ACM) has not been publicly disclosed; however, it has been reported that the ACM is twice as accurate as the ALCM-B.[16]

Advances in guidance technology may remove or reduce some of the limitations of current cruise missile guidance systems. The use of navigation signals from US Global Positioning System (GPS) or CIS GLONASS satellites could free cruise missiles from many of the limitations imposed by TERCOM guidance and provide better accuracy than TERCOM alone. The recent conversion of US nuclear ALCM-Bs into conventional land-attack missiles involved replacing their TERCOM guidance systems with one using GPS signals.[17] Current plans call for incorporating GPS receivers into conventional land-attack Tomahawks; however, the possible jamming of GPS signals and the uncertain survivability of satellites in a strategic conflict argues against relying on GPS for nuclear cruise missiles. Thus, strategic cruise missiles are likely to continue to rely on map-based or scene-matching guidance systems, although new types of sensors may be used to improve accuracy, reduce spurious emissions, and reduce vulnerability to jamming.[18] Furthermore, if a low flight altitude is to be maintained, it will still be necessary to fly presurveyed flight paths or to install a forward-looking terrain avoidance system (which could make the missile more vulnerable to detection).

Radar Cross Section

Much of the difficulty of detecting cruise missiles arises from their intrinsically small radar cross sections (RCS). The conventional wisdom is that the RCS of a cruise missile such as the US ALCM-B or Tomahawk is about 0.1 m^2.[19] For comparison, the RCS of a small jet airplane would be roughly 10 or 20 times greater.[20] This 0.1 m^2 figure appears to be roughly correct for orientations near nose-on and for frequencies above about 1 gigahertz (where many surveillance and air defense radars operate); however, while useful as a general guideline, it can be misleading if misapplied. In particular, care must be taken in applying this figure to lower frequencies. Figure 3 shows a simple estimate of the RCS of a Tomahawk-like cruise missile in the 5 to 30 megahertz frequency range used by over-the-horizon (OTH) radars. The RCS can be seen to vary by more than three orders of magnitude over this relatively narrow frequency range. The rapid RCS falloff, to below 0.01 m^2 at the low end of

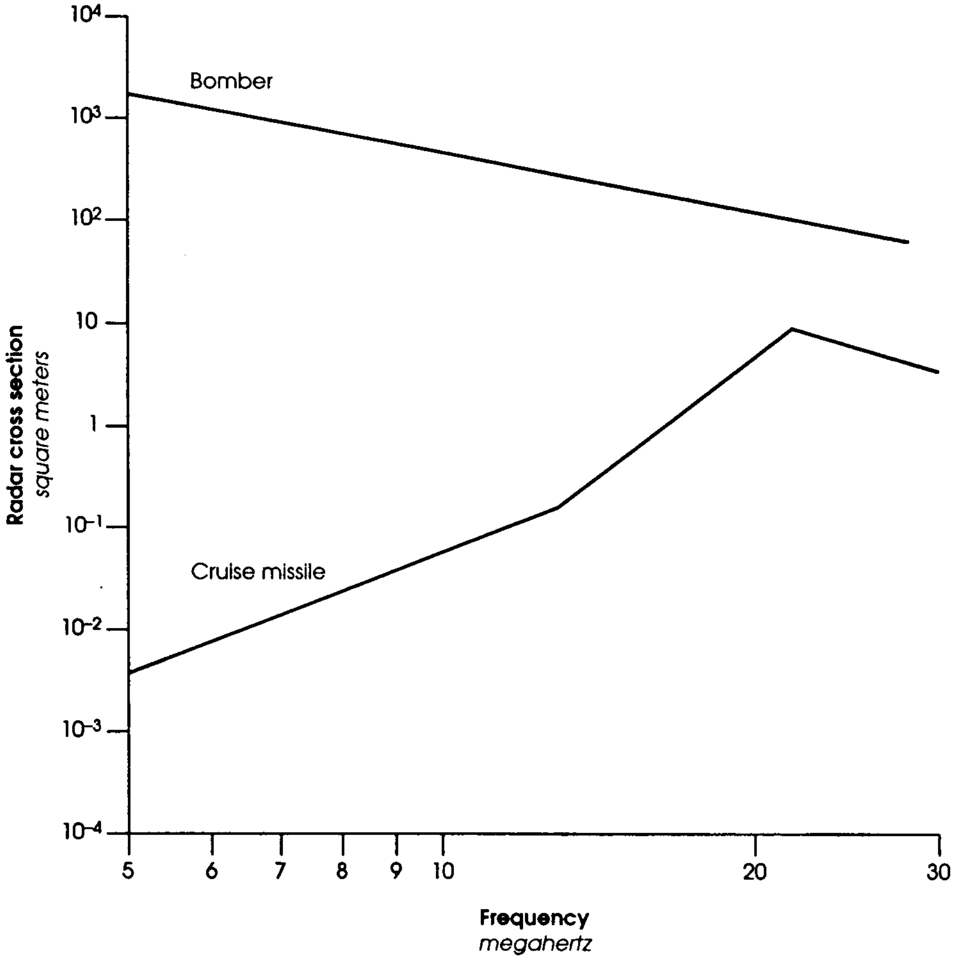


Figure 3: Radar cross sections (RCS) used in evaluating the performance of the OTH-B system. The cruise missile RCS is based on scaling figure 24.4 of Headrick (J.M. Headrick, "HF Over-the Horizon Radar", in Merrill I. Skolnik, ed., *Radar Handbook*, 2nd edition (New York: McGraw-Hill, 1990), pp.24.1–24.43), which gives the RCS of an oblong conducting rod of length 11 meters and width of 1 meter, and on unpublished calculations by Sally K. Ride, which model the SLCM body as a prolate spheroid following the procedures outlined in chapters 4 and 5 of George T. Ruck, Donald E. Barrick, William D. Stuart, and Clarence K. Krichbaum, *Radar Cross Section Handbook*, Volume 1 (New York: Plenum Press, 1970). The cruise missile RCS assumes that the radar looks down on the cruise missile from an angle of 30° above the horizon (the actual angle will generally be less than this, which will slightly reduce the RCS).

The bomber curve is taken from Fenster and represents a four-engine jet aircraft averaged over the front aspect quadrant and all polarizations. W. Fenster, "The Application, Design, and Performance of Over-the-Horizon Radars," *IEE International Conference Radar-77* (London: Institution of Electrical Engineers, 1977) pp.36–40.

this frequency range, occurs as a result of the missile entering the Rayleigh scattering regime, where the radar wavelength (60 meters at 5 megahertz) is much greater than the missile length. As we shall see, this has a significant impact on the effectiveness of OTH radars against cruise missiles.

The RCS of cruise missiles such as the Tomahawk or AS-15 is already lower than that of most piloted aircraft, with the possible exception of aircraft designed explicitly for stealth. Future cruise missiles are likely to have a reduced RCS as an important design criterion. This is already the case with the Advanced Cruise Missile. Such stealthy cruise missiles will provide an even greater challenge to air surveillance systems.

CURRENT CRUISE MISSILE WARNING CAPABILITIES

The US has long deployed systems intended to provide warning of bomber and ballistic missile attack. These systems, in particular those for ballistic missile warning, have proven to be highly reliable and effective. However, cruise missiles provide a fundamentally different, and in many ways more difficult, warning problem.

Cruise missiles are small, have a small radar cross section, and do not produce much heat or sound; that is, they are intrinsically stealthy. Future cruise missiles are likely to have significantly lower detection signatures. By flying low and maneuvering, cruise missiles can use terrain features for concealment, for limiting the detection ranges of ground-based sensors, and for exploiting gaps in warning or defense systems. In most cases, detection will have to be accomplished against a background of surface clutter. Furthermore, cruise missiles lack distinctive characteristics that would allow them to be easily distinguished from the many civilian aircraft which fly into and over the US every day. Even if detected, it is not possible to determine a cruise missile's target with certainty or whether it is conventional- or nuclear-armed. Submarine-launched SLCMs currently pose the greatest detection and warning challenge, since they can be launched from unknown locations by covert launchers and can approach from virtually any direction.

As of the mid 1980s, the United States, together with Canada, its partner in continental air defense activities, had little capability to detect cruise missiles penetrating North American airspace. The primary air surveillance systems at that time were the remnants of a once extensive system of northerly ground-based radars and the Joint Surveillance System (JSS), a system of ground-based radars around the perimeter of the United States that was jointly controlled by the Federal Aviation Administration (FAA) and the Air Force. Both of these systems had numerous low-altitude coverage gaps.

In the 1980s, the United States and Canada began deploying a new air surveillance system. The cornerstone of this system was to have been a 12 sector, $2.6 billion, over-the-horizon backscatter (OTH-B) radar system. The proposed coverage of this system is shown in figure 4. OTH radars "bounce" radar energy off the ionosphere and thereby circumvent limitations imposed by the earth's curvature. This enables them to detect targets at ranges of up to roughly 3,300 kilometers. The performance of OTH radars is critically dependent on the state of the ionosphere, which varies with the season, time of day, and level of solar activity. Furthermore, because OTH radars cannot look towards the magnetic poles due to auroral ionospheric disturbances, a new line of ground-based radars is being constructed to cover the northern gap in OTH coverage. This system, which replaces the old Distant Early Warning line, is known as the North Warning System (NWS) and its planned high-altitude coverage is also shown in figure 4 (its low-altitude coverage is briefly discussed below).[21]

The full US OTH-B system, together with the NWS, would have provided complete coverage of the air approaches to North America against bomber-sized targets. However, it now appears unlikely that the OTH-B system will ever be completed. Only the six sectors located on the east and west coasts have been completed; construction on the other six sectors has been stopped and is unlikely to resume.[22] This leaves large gaps in OTH-B coverage, not only looking south, but also close-in off both the east and west coasts. Furthermore, as a result of the declining threat posed by the CIS and reductions in the US defense budget combined with the OTH-B system's problems detecting cruise missiles (discussed below), the already completed east and west coast sites have either been deactivated or reduced to running on only a part-time basis.[23]

However, even if the US OTH-B system were completed as planned it would not provide a reliable warning capability against small-scale cruise missile attacks. The OTH-B system was originally intended for detection of Soviet

Figure 4: Radar coverage of the planned US 12 sector OTH-B system. Sectors shown with dashes were planned but have not been built. Also shown (circles) is the high-altitude coverage of the 15 long-range FPS-117 radars of the North Warning System. The high-altitude coverage of the FPS-117 radars of an Alaskan radar system known as SEEK IGLOO is also shown.

bombers and it would be effective against such targets. With the unexpectedly rapid emergence of the Soviet cruise missile threat, the US Air Force conducted tests in 1988 using modified Firebee drones to simulate cruise missiles. Initially, these tests were reported to indicate that the OTH-B system had some capability to detect cruise missiles, and plans were made to deploy the west coast OTH-B sectors with lengthened receive antennas in order to improve performance against cruise missiles.[24] However, the US Air Force subsequently dropped cruise missile detection as a goal for the OTH-B system, citing the large costs of the improvements that would be required to give it such a capability.[25]

OTH-B's difficulties in detecting cruise missiles arise primarily from the missiles' small sizes. While a cruise missile can, at certain combinations of orientation, polarization, and frequency, have an RCS approaching or exceeding that of an airplane, under most circumstances it will be much smaller. As illustrated in figure 3 and discussed in appendix B, the short cruise missile length results in a very small radar cross section in the lower part of the OTH-B's frequency range. As a result, at night, when OTH operation is often restricted to the lower end of its frequency range, the cruise missile RCS may become too small for the OTH-B system to detect. Figure 5 shows the results of a simple estimate of the OTH-B system's performance;[26] it shows the signal-to-noise ratio as a function of range for the month of October for both a bomber-sized target and for a Tomahawk-like cruise missile. This figure, along with the more detailed discussion in appendix B, suggests that while the OTH-B system is capable of detecting cruise missiles at certain times, it may have little or no capability against them at night.

The North Warning System may also be vulnerable to undetected penetration by low-flying cruise missiles. While a definitive assessment of the NWS's capability against low-altitude targets requires a detailed knowledge of the radars' siting and the geography, the number of radar sites appears to be insufficient to prevent low-altitude coverage gaps.[27] This is consistent with statements by military officials concerning the NWS.[28] However, it is important to note that the presence of low-altitude coverage gaps does not necessarily mean that these gaps can be exploited by cruise missiles. Such gaps are likely to occur in areas of rough terrain, where cruise missiles may need to fly at higher than normal altitudes. On the other hand, any cruise missiles that were detected would be in view for only a few minutes and the system could therefore provide little if any tracking data for assessing the nature of an attack. Current plans call for the NWS to be backed up by the deployment of airborne warning and control system (AWACS) aircraft to bases in northern Canada in a crisis.

There are other sensors that could contribute to a cruise missile warning system. The Joint Surveillance System currently provides nearly complete coverage of the US perimeter at altitudes above 10,000 feet, and plans call for

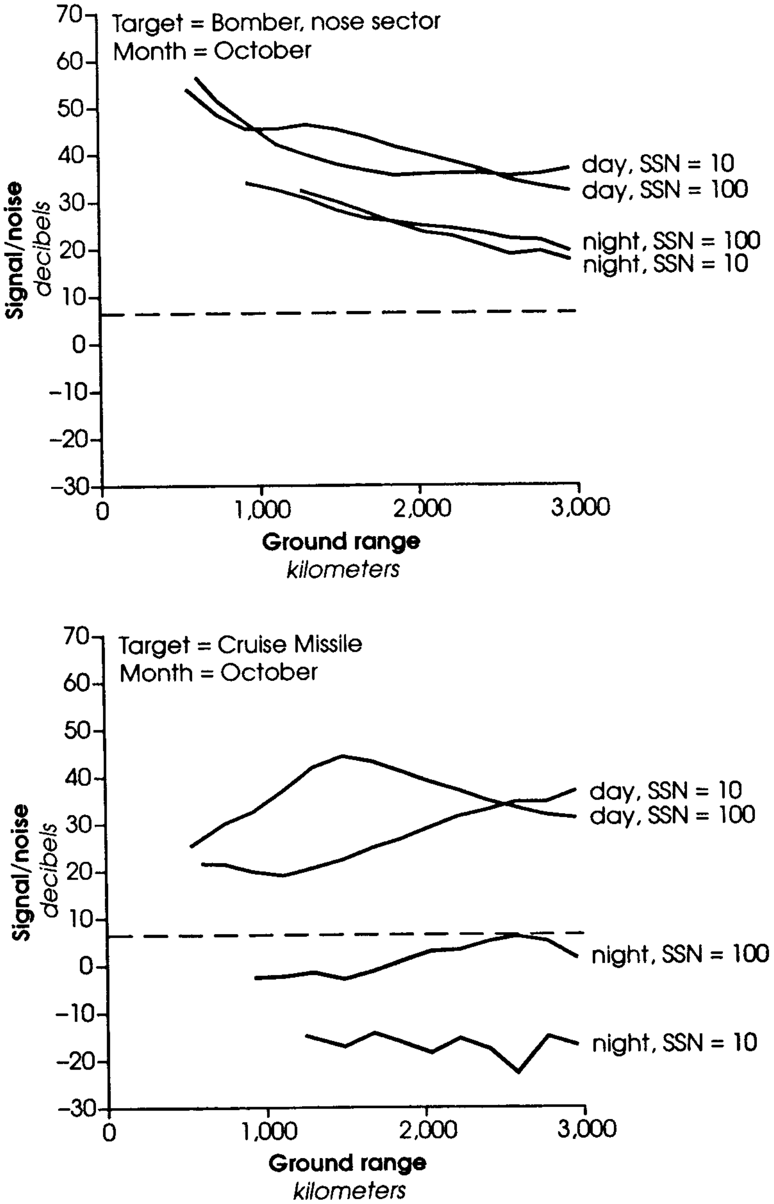


Figure 5: OTH S/N performance against a bomber target (viewed from the nose-on sector) and a Tomahawk-like cruise missile (viewed from 30° above nose-on) for typical autumn conditions. Curves are plotted for day (1 pm) and night (3 am), and for high and low levels of solar activity (sunspot number (SSN) of 10 indicates low solar activity and SSN = 100 indicates high solar activity). The dashed line at S/N = 4 (6 decibels) is an estimate of the minimum S/N required for detection by forming tracks. Calculations are discussed in appendix B.

the JSS radars to be upgraded to increase their capabilities against low RCS targets.[29] The US Air Force operates 34 E-3 AWACS radar aircraft; these together with US Air Force interceptor aircraft could play a crucial role by providing an attack confirmation and target identification capability. However, the number of AWACS aircraft is far too small to maintain a continuous surveillance perimeter around the United States, even if these airplanes were not needed for other purposes.[30] The recent surge of interest in intercepting drug smuggling aircraft has also resulted in a growing network of radars deployed aboard airplanes and aerostats (tethered balloons) along the southern US border.[31] The US Navy's network of acoustic underwater sensors and other antisubmarine warfare (ASW) capabilities could play a very important role both by tracking CIS submarines and by detecting the launches of SLCMs (by detecting the underwater ignition of their rocket boosters). Indeed, these ASW capabilities appear to be the United States' most effective warning capability against SLCMs at present. However, they cannot provide warning against ALCMs, and their capability to keep pace with the quieting of CIS submarines and with quieter methods of launching SLCMs is uncertain.[32]

Overall, current and likely near-term US air surveillance systems appear to have little capability to provide reliable warning of cruise missile attacks. It is unlikely that the CIS has any greater capabilities against US cruise missiles. Furthermore, existing capabilities on both sides will degrade if longer-range, stealthy cruise missiles are deployed.

CRUISE MISSILES AS SURPRISE ATTACK WEAPONS

The inability of the United States and the CIS to reliably detect cruise missiles in flight raises the possibility that a small-scale cruise missile attack could go entirely undetected, thereby creating an entirely new threat of zero-warning nuclear surprise attack. The primary concern is not that cruise missiles would be used directly in large-scale counterforce attacks, such as an attack on ICBM silos, but that they might be used in a small-scale "leading-edge" or "precursor" attack on a set of critical targets immediately in advance of a full-scale attack by ballistic missiles.[33] Such a leading-edge attack would be directed against key targets that rely on or could exploit the short amount of warning time that would be available in a ballistic missile attack. The most important such targets are strategic bomber bases and key command and control facilities.

The few minutes of warning available in an attack by ballistic missiles on standard trajectories are in principle enough to allow most or all of a US or former Soviet bomber force that is on alert to escape. However, as a result of President Bush's recent arms initiatives, US strategic bombers are no longer kept on alert (Soviet bombers were already on a nonalert status), although this change could be quickly reversed if international tensions increased. Thus, at present, both US and CIS strategic bombers are vulnerable to any form of nuclear attack for which only tactical warning is obtained. However, if international tensions rise to the point that such an attack becomes conceivable, some of the bomber force would almost certainly be restored to alert status.

Bombers and airbases are soft targets, and in a zero-warning attack a single nuclear explosion would likely destroy all of the bombers at a given airbase. At present, the US strategic nuclear bomber force is deployed at only 13 bases and it appears that CIS strategic bombers are deployed at only four bases.[34] At least for US, this figure is unlikely to increase and will probably decrease as B-52Gs are retired and replaced by less numerous B-2s. Thus an attack by 13 cruise missiles (or 26 if two are assigned to each target) against a nondispersed US bomber force potentially could destroy the entire bomber force on the ground.[35] As few as four to eight weapons could be required for an attack on the nondispersed bomber force of the CIS.

The other important set of potential leading-edge attack targets are key strategic command and control facilities, such as major command centers, strategic communications facilities, strip-alert aircraft (such as airborne command posts and launch control centers), ballistic missile early-warning radars, and satellite ground stations for early-warning satellites. The precise number of targets that might be attacked, as well as the effects of such an attack, are intrinsically much more difficult to determine than in the case of an attack on the bomber force. However, in an attack against the United States, the most critical targets appear to be the relatively small number of major command centers[36] and bases of strip-alert aircraft.[37] Assuming double targeting, an attack by 30 to 40 cruise missiles would be required to destroy these targets. Even against a nonalerted command system, an attacker could not be certain that all critical command centers would be destroyed, because certain targets, such as the Looking Glass aircraft (if airborne) and mobile ground command centers (if dispersed), could not be targeted, and there may be critical command arrangements or facilities of which the attacker is not aware. Nevertheless, such an attack could disrupt the response of the US strategic command and control system, perhaps to the point of endangering the launch on warning or attack of the US ICBM force. Even a considerably smaller attack limited to a few of these key targets could potentially be very disruptive. Very little detailed information is available on the CIS command and control system, but it is not unreasonable to assume that a similar number of weapons would have an equally disruptive effect in an attack on the strategic command and control system of the CIS.

Thus in a peacetime "bolt out of the blue" situation, of order 15 to 30 cruise missiles could destroy the entire US or CIS bomber force on the ground or disrupt the workings of US or CIS command systems sufficiently to endanger the prompt launch of their ICBM forces. Roughly 30 to 60 missiles would be required to attack both sets of targets simultaneously, potentially threatening the prompt destruction of two out of the three legs of either country's strategic triad. Such an attack could be launched from as few as three submarines or three to six bombers.

The feasibility, plausibility, and effectiveness of a cruise missile surprise attack must be kept in perspective. Even a completely successful cruise missile surprise attack could not prevent retaliation, because, at least for the United States, several thousand warheads would be at sea on ballistic missile submarines. The CIS keeps a smaller fraction of its ballistic missile submarine force at sea on a routine basis, but it is likely that at least several hundred CIS warheads would be at sea.

In addition, the leading-edge attack works most effectively in the situation that is least plausible—an attack without strategic warning. In the midst of a severe crisis, or if there were a sharp deterioration in US–CIS relations, a cruise missile surprise attack would become more difficult to mount and would likely be much less effective. The strategic bomber forces could be dispersed to a larger number of bases, perhaps as many as 60–75,[38] not all of which might be known to the attacker. This would, at a minimum, have the effect of increasing the number of cruise missiles required, even if only a single missile were used against each base. While 60–75 cruise missiles could still be launched by as few as three to four submarines or five to ten bombers, the increased number of missiles and the greater diversity of flight paths required would increase the probability that the attack would be detected. Nevertheless, as long as the locations of the dispersal bases were known the bomber forces would remain vulnerable.

While the survivability of an alerted bomber force might only be marginally increased, an alerted command and control system could be much more difficult to cripple. In this situation, command authority is likely to be widely dispersed; mobile and alternate command posts are likely to be fully staffed and dispersed; and strip-alert aircraft could be placed on airborne alert. An attack on the fixed command posts might accomplish little in this situation. Nevertheless, a cruise missile surprise attack might still be the most disruptive possible form of attack on the strategic command and control system. The ability of either country to launch their ICBM force under attack may be less certain in this case than in any other attack scenario.

On the other hand, an attack planner contemplating a cruise missile surprise attack would be confronted by the risk of premature detection or other failure. The missile-launching submarines or bombers could be detected moving to their launch points. In the case of SLCMs, the launches themselves, which must be conducted under very tight time constraints, could be detected either by a nearby ship, submarine, or aircraft, or in the case of a CIS submarine, by the extensive network of US underwater acoustic sensors. Even in the absence of an air surveillance system capable of reliably detecting cruise missiles, a few missiles might still be detected either in flight or as the result of crashes. Such premature detections could give the intended target country hours of warning in which to prepare or preempt.

There are also potentially serious communications and command and control difficulties associated with a cruise missile surprise attack, particularly one using SLCMs. A submarine that has reached its attack position undetected may be unable to report this information or cancel the attack if it believes it has been detected. SLCM-launching submarines must be forward deployed (at least with present SLCM ranges) if they are to be able to cover the entire United States or the CIS. In the CIS case, such a forward deployment would run counter to their long-standing tradition of maintaining tight command

and control over their strategic nuclear submarines.[39] Maintaining a cruise missile surprise attack capability on station at all times could also place a substantial burden on either country's attack submarine force. On the other hand, surging a SLCM attack force into attack positions when a crisis appears imminent might require several weeks, by which time the crisis may already have passed or escalated.

These considerations may lead attack planners to the conclusion that a leading-edge attack is either too problematic or too costly to develop into a reliable capability for it to figure into their nuclear war plans. However, both countries are likely to retain a substantial capability to launch a cruise missile surprise attack, even if they are not currently interested in the further development of such a capability. Quieter submarines, longer-range and stealthier ALCMs and SLCMs, and quieter means of launching SLCMs are all militarily desirable for reasons other than launching a cruise missile surprise attack. Moreover, before Bush's and Gorbachev's mutual unilateral withdrawal of nuclear SLCMs from deployment, there was not necessarily a clear cut demarcation between different levels of threat, as the capability to launch a cruise missile surprise attack could develop gradually, without a major distinctive leap in capability. For example, while the Soviet development and deployment of a quiet, dedicated SS-N-21 guided-missile submarine and its deployment off US shores would have posed a clear threat, it was difficult or impossible to know if attack submarines patrolling off US coasts were armed with many torpedoes and a few cruise missiles, or vice versa (at least in the absence of an intrusive arms control verification regime). Furthermore, land-attack SLCMs deployed to cover US or Soviet targets for any reason, even for purely retaliatory purposes, may well be deployed in a manner similar to what would be used for a surprise attack.[40] While Bush's and Gorbachev's withdrawal of nuclear SLCMs to on-shore storage was therefore an important step in reducing the threat of a cruise missile surprise attack, it is far from a complete solution because the nuclear SLCMs could be redeployed, there is no verification of their withdrawal, and nuclear ALCMs remain deployed.

SHOULD THE SURPRISE ATTACK CAPABILITIES OF CRUISE MISSILES BE A CONCERN?

If, as we have argued, the surprise attack capabilities of cruise missiles pose a potentially very serious threat to stability, why has this problem received so little attention? In part, this may be due to the widely held perception that cruise missiles are stabilizing weapons and to a lack of knowledge about deficiencies in air surveillance capabilities. However, at least in the US case, another important factor is that the CIS cruise missile threat is of relatively recent origin and has developed during a period of improving US–CIS relations.

An argument can be made that the United States and the CIS should simply continue to neglect this problem. A nuclear war between these two countries seems nearly inconceivable today. Even if such a war were to occur, it would almost certainly be preceded by a period of deteriorating relations that would provide an opportunity to take measures to address the threat. Moreover, given all of the uncertainties involved in a cruise missile surprise attack, it is far from clear that if either country decided to launch a nuclear attack on the other that this is the approach they would choose. Thus, it could be argued that, in the current situation, the best course of action is to simply ignore the problem, particularly if solutions appear to be difficult or expensive.

However, delaying taking action unless and until the US–CIS relationship deteriorates is risky because such a change could occur too quickly for an effective response. In such a situation, cruise missiles not only could pose a direct military threat, but could also lead to serious distortions of defense policy. Given the right set of political and external circumstances, the cruise missile surprise attack threat could easily become another "window of vulnerability," only more severe because it affects two legs of the triad.

While it is unclear whether, even in a serious crisis, either side would ever attempt to use cruise missiles as surprise attack weapons, such an attack may seem implausible only because we are conditioned to think in terms of very rapid short-warning ballistic missile attacks. In such a ballistic missile attack, the attacked country sees the attack coming, and the success of the attack (measured in nuclear forces destroyed) depends on whether the attacked country responds in time. In a cruise missile attack, success depends on the attacked country not seeing the attack coming. It is unclear, and undeterminable, which is the bigger gamble. However, it is clear that the likelihood of an attacker attempting either type of counterforce surprise attack is, at least to some degree, dependent on the vulnerability of the forces of each country and the state of their warning systems. It is in the interest of both countries to take whatever steps are possible to foreclose either type of surprise attack.

Another concern is that efforts that might be made to improvise a warning capability in a crisis could lead to dangerous false alarms. Even though a large-scale ballistic missile launch is an unambiguous event with a strong signature, and even though both countries have been operating ballistic missile warning systems for many years, false alarms of ballistic missile attack remain a concern. Such false alarms are easily resolved during periods of low international tensions, but would be much more worrisome and dangerous during a serious crisis.

Cruise missiles pose a much more severe false alarm problem. The detection of cruise missiles will inevitably have to be accomplished against a clutter background, and cruise missiles can easily be confused with a variety of military and civilian aircraft (and vice versa). Ideally, a cruise missile warning system would undergo a long period of operation and debugging during a period of low US–CIS tensions. Attempting to rapidly deploy and operate a cruise missile warning system as a result of a deterioration in US–CIS relations could produce false alarms that could increase the risk of inadvertent nuclear war.

Thus, even if cruise missile deployments are seen as relatively benign in the current strategic environment, they could take on an altogether different appearance should a serious crisis ever occur between the United States and the CIS. In this situation, the surprise attack capability of nuclear SLCMs could become an extremely destabilizing factor. In addition, the capability of cruise missiles to threaten the survivability of elements of their strategic nuclear forces could hinder the efforts of the United States and the CIS to achieve deep reductions in their strategic nuclear arsenals, as survivability will become increasingly important as force size is reduced.

CONCLUSION

Despite their image as stabilizing weapons, cruise missiles are potentially among the most destabilizing of all strategic nuclear weapons because neither the United States nor the CIS has systems capable of providing reliable warning of small-scale cruise missile attacks. Fundamentally, nuclear deterrence remains a cornerstone of the policy of both the United States and the CIS, and their nuclear deterrents are built around a triad of nuclear forces, two of the three legs of which rely on tactical warning for survivability. As long as they continue to rely on nuclear deterrence built around such forces, they should not neglect the warning systems on which their survivability is dependent. Because of the long lead times that might be involved in possible responses to this problem, the time to do something about it is now, before a crisis or a deterioration in US–CIS relations occurs. Of course, the prospects for addressing this problem depend on the cost and feasibility of potential solutions, which we will consider in a subsequent paper.[41]

ACKNOWLEDGEMENTS

The authors thank Sidney Drell, Lisbeth Gronlund, David Wright, and two anonymous reviewers for useful discussions and comments.

NOTES AND REFERENCES

1. George N. Lewis and Theodore A. Postol, "Nuclear Cruise Missiles After the Cold War," submitted to *Science & Global Security.*

2. The dividing line between short- and long-range cruise missiles is set at 600 kilometers for both ALCMs and SLCMs by the START agreement. The United States had previously deployed a number of older long-range cruise missiles. See Kenneth P. Werrell, *The Evolution of the Cruise Missile* (Washington DC: US Government Printing Office, 1983).

3. It has recently been reported that the United States converted some of its nuclear ALCM-Bs into conventional ALCM-Cs, and that a small number of these ALCM-Cs were used against Iraq during the Gulf War. "ALCMs in Iraq," *Aviation Week and Space Technology* **136**, 3, 20 January 1992, p.19; "Air Force Launched 35 ALCMs on First Night of Gulf Air War," *Defense Daily,* 17 January 1992, p.88.

4. For general discussions of the characteristics of modern long-range cruise missiles, with an emphasis on the Tomahawk and the US ALCM-B see: Ronald Huisken, *The Origin of the Strategic Cruise Missile* (New York: Praeger, 1981) pp.3–14; John C. Toomay, "Technical Characteristics," in Richard K. Betts, ed., *Cruise Missiles: Technology, Strategy, Politics* (Washington DC: Brookings, 1981) pp.31–52; and Kosta Tsipis, "Cruise Missiles," *Scientific American* **236**, 2, February 1977, pp.20–29.

For characteristics of current US and CIS SLCMs and ALCMs, including shorter range missiles, see appendixes 1 and 2 of Valerie Thomas, "Verification of Limits on Long-Range Nuclear SLCMs," *Science & Global Security* **1**, 1–2, 1989, pp.27–57; and appendixes A and B of Thomas K. Longstreth and Richard A. Scribner, "Verification of Limits on Air-Launched Cruise Missiles," in Frank von Hippel and Roald Z. Sagdeev, eds., *Reversing the Arms Race: How To Achieve and Verify Deep Reductions in the Nuclear Arsenals* (New York: Gordon and Breach, 1990) pp.181–235.

5. The quote is from President Bush's announcement of the US arms initiative. For the texts of President Bush's announcement and President Gorbachev's response, see "A New Era of Reciprocal Arms Reductions: Texts of President Bush's Nuclear Initiative and Soviet President Mikhail Gorbachev's Response," *Arms Control Today* **21**, 8, October 1991, pp.3–6.

6. US Department of Defense, *Soviet Military Power 1989* (Washington DC: US Government Printing Office, 1989) p.49.

7. The significance of operational range can be seen by comparing the operational ranges of the conventional ship-attack and land-attack versions of the Tomahawk. Although these missiles are similar in total weight and fuel weight, their operational ranges vary by almost a factor of three (1,300 kilometers for the land-attack version, 450 kilometers for the ship-attack version). This difference is due to the need for the ship-attack version to fly an extensive search pattern in order to acquire its target.

8. This is not a fully optimized range because the variation in specific fuel consumption with speed is not taken into account in determining the optimum speed.

9. This large correction factor may be primarily due to the need to overfly mapped areas for guidance updates. The US Navy has stated that the use of the GPS navigation system on conventional Tomahawks (which will remove the need to overfly premapped terrain in order to update their guidance systems) will increase their standoff range by up to 20 percent. See the statement of Rear Admiral William C. Bowes (Director, Cruise Missiles Project) before the Defense Subcommittee of the House Appropriations Committee, 21 April 1988, p.11.

10. The US Advanced Cruise Missile, with its reported 4,000 kilometer range, would be capable of reaching Moscow from the North Pole.

11. TERCOM determines the cruise missile's location by using a radar altimeter and barometric measurements to obtain terrain height profiles that are compared with presurveyed terrain height profiles. This information is then used to correct drift errors in the inertial guidance system. Tsipis, "Cruise Missiles,"; Joe P. Golden, "Terrain Contour Matching (TERCOM): A Cruise Missile Guidance Aid," in *Image Processing for Missile Guidance, Proceedings of the Society of Photo-Optical Instrumentation Engineers* **238**, 1980, pp.10–18; and William R. Baker and Roger W. Clem, *Terrain Contour Matching Primer*, ASD-TR-77-61, Directorate of Systems Engineering, Aeronautical Systems Division, Wright-Patterson Air Force Base, August 1977.

12. A circular error probable (CEP) of "about 250 feet" (76 meters) was given by Commodore Roger Bacon in Congressional testimony (US House of Representatives, Armed Services Committee, Department of Defense Authorization Hearings for Fiscal Year 1985, part 2, p.392), although some CEP estimates are as low as 30 meters (Thomas B. Cochran, William M. Arkin, and Milton M. Hoenig, *Nuclear Weapons Databook, Volume I: US Nuclear Forces and Capabilities* (Cambridge, Massachusetts: Ballinger, 1984) p.187.

The conventionally armed land-attack variants of the Tomahawk add a digital scene matching area correlator (DSMAC) terminal guidance system which reduces the CEP to about 25 feet. Jon R. Carr and James S. Sobek, "Digital Scene Matching Area Correlator," in *Image Processing for Missile Guidance, Proceedings of the Society of Photo-Optical Instrumentation Engineers* **238**, 1980, pp.36–41.

13. A 150 kiloton warhead detonated at a height of 100 meters and a ground range of 80 meters will produce a maximum overpressure well in excess of 700 atmospheres (10,000 psi). See Samuel Glasstone and Philip J. Dolan, *The Effects of Nuclear Weapons* (Washington DC: US Government Printing Office, 1977) pp.110–111. Current US ICBM silos are believed to be hardened to 130–200 atmospheres. Barbara G. Levi, Mark Sakitt, and Art Hobson, eds., *The Future of Land-Based Strategic Missiles* (New York: American Institute of Physics, 1989) p.32.

14. The complexity of this guidance approach may also translate into reduced reliability relative to ballistic missiles. However, it is likely that reliability improvements will occur as more operational experience with land-attack cruise missiles is gained.

15. The missile uses its radar altimeter to determine its altitude above ground. Flight altitudes of 20 meters over water, 50 meters over moderately hilly terrain, and 100 meters over mountains have been cited for the Tomahawk. Tsipis, "Cruise Missiles," p.24. Another paper cites data that indicates that the Tomahawk has a "command altitude" of 98 meters over moderate terrain and 139 meters over rough terrain. A new wing for the Tomahawk is discussed that would reduce these figures to 60 meters and 113 meters. B.J. Kuchta, "Technology Advances in Cruise Missiles," AIAA Paper No. 81-0937, AIAA 1981 annual meeting, Long Beach, California, 12–14 May 1981.

16. Longstreth and Scribner, "Verification of Limits on Air-Launched Cruise Missiles," p.214. However, laser light warnings have been observed on the Advanced Cruise Missile, leading to speculation that it may use a laser-based system for navigation. "Air Force Displays Advanced Cruise Missile for First Time," *Aviation Week and Space Technology* **132**, 20, 14 May 1990, p.30.

17. "Air Force Launched 35 ALCMs," *Defense Daily*, 17 January 1992.

18. Methods under consideration for advanced conventional long-range cruise missiles include laser radar scene matching, imaging infrared, and synthetic aperture radar. Norman Friedman, *World Naval Weapons Systems 1991/92* (Annapolis, Maryland: Naval Institute Press, 1991), p.123. For an overview of approaches for updating inertial guidance systems, see John T. Ritland, "Survey of Aided-Inertial Navigation Systems for Missiles," *AIAA Guidance, Navigation, and Control Conference*, Boston, Massachusetts, 14–16 August 1989, pp.608–617.

19. For example, the 0.1 m^2 figure is cited in John W. R. Lepingwell, "Soviet Strategic Air Defense and the Stealth Challenge," *International Security* **14**, 2, Fall 1989, p.85. We will consider in more detail the radar cross section of a Tomahawk-like cruise missile, how this RCS can be reduced, and some of the problems involved in detecting low RCS targets in a subsequent paper (see note 1).

20. For a short, representative list of aircraft RCS values, see Merrill I. Skolnik, *Introduction to Radar Systems*, 2nd edition (New York: McGraw-Hill, 1980) p.44.

21. The first phase of NWS deployment consists of 15 long-range FPS-117 radars, all of which have been installed. A second phase consisting of 39 short-range, "gap-filling," FPS-124 radars is to be deployed in the early to mid 1990s. "US, Canada Agree To Renew NORAD Pact," *Aviation Week and Space Technology* **134**, 17, 29 April 1991, p.71.

22. The US Department of Defense included $242 million for OTH-B in its 1991 Drug Interdiction and Counterdrug Activities budget. Most of this money would have been used to procure one of the south-looking sectors of the central OTH site. However, Congress did not approve this request. US General Accounting Office, *Over-the-Horizon Radar: Better Justification Needed for DoD System's Expansion*, GAO/NSIAD-91-61 (Washington DC: Government Accounting Office, January 1991). See also George Leopold, "Pentagon Seeks Drug Funds to Finance Portion of OTH-B Radar," *Defense News* **5**, 8, 19 February 1990, p.12.

23. Currently, the east coast site is only operating eight hours per day, five days per week, and the west coast site has been mothballed. If necessary, the west coast site could be reactivated in six months. Neil Munro, "DoD to Scrap Billion Dollar Over-the-Horizon Coastal Radars," *Defense News* **6**, 3, 18 January 1991, p.6; "USAF Weighs Plan for Limited OTH-B Operations in Maine," *Aviation Week and Space Technology* **134**, 17, 29 April 1991, p.69; "USAF Limits OTH-B on East Coast, Mothballs West Coast Site," *Aviation Week and Space Technology* **134**, 22, 3 June 1991, p.24; William C. Hidlay, "Maine Defense Radar To Run Only Part Time," *Boston Globe*, 28 May 1991, p.60.

24. David Hughes, "Tests Verify OTH-B Radar's Ability to Detect Cruise Missiles," *Aviation Week and Space Technology* **128**, 12, 21 March 1988, pp.60–65. See also the testimony of General Moorman, US House of Representatives, Committee on Appropriations, Department of Defense Appropriations for Fiscal Year 1989, part 6, pp.545, 562–563. However, other statements concerning OTH capability against cruise missiles are less than confidence-inspiring, such as that of the NORAD Commander-in-Chief, General Piotrowski: "Our analysis shows that even under the worst conditions for detecting cruise missiles, the likelihood of OTH-B's detecting at least one out of ten of them is high enough that the Soviets probably couldn't count on bringing off a surprise attack." James W. Canan, "The Big Hole in NORAD," *Air Force Magazine* **72**, 10, October 1989, pp.54–59.

25. George Leopold, "Price Tag Changes OTH-B Mission," *Air Force Times*, 26 March 1990; Donald Woutat, "Radar Site's Wide Eye May Shift to Drug War," *Minneapolis Star Tribune*, 15 February 1990, p.1.

26. These graphs were produced using the procedure outlined in J.M. Headrick, "HF Over-the-Horizon Radar," in Merrill I. Skolnik, ed., *Radar Handbook*, 2nd edition (New York: McGraw-Hill, 1990) and are discussed in more detail in appendix B.

27. The total length of the line covered by the NWS appears to be about 5,500 kilometers and therefore each of the 54 radars must cover an average radius of about 51 kilometers. The gap-filling radars are on towers 20 to 100 feet high (US House of Representatives, Armed Services Committee, Department of Defense Authorization for Fiscal Year 1985, part 4, p.1270). If we assume that the average radar antenna is tower-mounted at a height of 30 meters and that it must provide coverage down to 60 meters in altitude, then the smooth earth detection range is 54.5 kilometers. Heilenday cites the following as the fractional reduction of horizon detection range (relative to a smooth earth); flat terrain–0.85; rolling terrain–0.65; hilly terrain–0.5, see Frank Heilenday, *Principles of Air Defense and Air Vehicle Penetration* (Washington DC: CEE Press Books, 1988), p.4.6. If we assume that on average the fractional reduction is 0.75, then the actual detection radius is about 41 kilometers and this range would need to be reduced further in order to provide some overlap between adjacent radars. This result is consistent with Delaney's estimate that a ground-based radar can detect a 60 meter altitude target at a range of 30 to 45 kilometers. William P. Delaney, "Air Defense of the United States," *International Security* **13**, 1, Summer 1990, pp.181–211.

[redacted]

28. The NWS is described as reducing rather than removing the low-altitude coverag gaps of the Distant Early Warning (DEW) line. See the testimony of Maj. Gen. John A Shaud, US House of Representatives, Armed Services Committee, Department o Defense Authorization for Fiscal Year 1985, part 4, p.1268. Canadian defense ministe Perrin Beatty is reported to have said that CIS cruise missiles could underfly th NWS, see David Hughes, "USAF Will Develop Major Radar Upgrade for its E- AWACS Fleet," *Aviation Week and Space Technology* **129**, 4, 23 January 1989 pp.45–49.

29. Current plans call for this system to be upgraded with more advanced radars. Th requirements for these new ARSR-4 radars include the capability to detect a 0.1 m target at 160 kilometers (100 miles). General Electric's proposed ARSR-4 radar is sai to "closely resemble" the FPS-117 radar it is supplying for the NWS. Philip J. Klass "Four Radar Firms Vie for FAA/USAF Air Surveillance Radar Contract," *Aviation Week and Space Technology* **128**, 21, 23 May 1988, pp.93–99.

30. The AWACS aircraft are primarily intended for theater use. However, eight o them are currently designated for continental defense missions in wartime. See Arthur Charo, *Continental Air Defense: A Neglected Dimension of Strategic Defense*, CSIA Occasional Paper No. 7 (Cambridge, Massachusetts: Center for Science and International Affairs, Harvard University, 1990), p.19. The US Navy also has over 100 E2-C Hawkeye radar surveillance aircraft that are also primarily assigned to tactical missions.

31. US General Accounting Office, *Drug Smuggling: Capabilities for Interdicting Private Aircraft Are Limited and Costly*, GAO/GGD-89-93 (Washington DC: General Accounting Office, June 1989).

32. One way to significantly reduce the noise made by a submarine-launched missile is to enclose it in a buoyant capsule that pops it out of the water before the rocket engine is ignited. The US Sea Lance submarine-launched antisubmarine missile reportedly was to use such an approach to meet requirements for stealthy operation. See Friedman, *World Naval Weapons Systems 1991/92*, p.691.

33. Theodore A. Postol, "Banning Nuclear SLCMs—It Would Be Nice If We Could," *International Security* **13**, 3, Winter 1988/89, pp.191–202.

34. For US bomber bases, see Longstreth and Scribner, "Verification of Limits on Air-Launched Cruise Missiles," p.202. This count excludes Loring Air Force Base in Maine, where conventionally armed B-52Gs are deployed, and the recently deactivated FB-111 bombers at the Pease and Plattsburgh Air Force Bases. According to a START treaty Memorandum of Understanding, Soviet heavy bombers are based at two bases in Ukraine, one in Kazakhstan, and one in Russia. See Robert S. Norris and William M. Arkin, "Nuclear Notebook," *Bulletin of the Atomic Scientists* **48**, 1, January/February 1992, p.48.

35. Other possible strategic force targets include bases of tanker aircraft, ICBM launch control centers (particularly if arms control reductions result in a significant reduction of these from their pre-START total of 100), or the garrisons of mobile missiles that dashed for safety on warning if such missiles were to be deployed in such a way that there were more than a few missiles per garrison.

36. Carter lists nine major command centers in the US which he considers as category one targets. These are the National Military Command Center (in the Pentagon); the Alternate National Military Command Center (Fort Ritchie, Maryland); the White House; the Strategic Air Command headquarters (HQ) (Omaha, Nebraska); the

NORAD HQ (Colorado Springs, Colorado); the HQ of the Commander-in-Chief, Atlantic (CINCLANT) (Norfolk, Virginia); the HQ of the Commander-in-Chief, Pacific (CINCPAC) (Oahu, Hawaii); Camp David (Maryland); and Mount Weather (Virginia). Ashton B. Carter, "Assessing Command System Vulnerability," in Ashton B. Carter, John D. Steinbruner, and Charles A. Zraket, eds., *Managing Nuclear Operations* (Washington DC: Brookings Institution, 1987), p.561.

37. These aircraft (command posts, airborne launch control centers, and airborne communications relay aircraft) were, at least until recently, kept on strip-alert ready to be launched on warning of attack. It is possible that some or all of these aircraft have now been removed from alert status, although they could be quickly put back on alert if international tensions increased. These aircraft include: the National Emergency Airborne Command Post (NEACP) and a Post-Attack Command Control System (PACCS) relay aircraft at Grissom Air Force Base (AFB); Indiana (although the NEACP plane that the President would use is kept in Indiana, the NEACP home base is said to be at Blytheville [now Eaker] AFB, Arkansas); two airborne launch control centers (ALCC) at Minot AFB, North Dakota; another ALCC and an auxiliary ABNCP (airborne command post) aircraft at Ellsworth AFB, South Dakota; a PACCS relay aircraft at Rickenbacker AFB, Ohio; and an auxiliary ABNCP and the non-airborne Looking Glass aircraft at Offutt AFB in Nebraska. The airborne command posts of CINCLANT in Norfolk, Virginia and of CINCPAC in Hawaii are also likely targets. See Carter, "Assessing Command System Vulnerability," and Bruce G. Blair, *Strategic Command and Control: Redefining the Nuclear Threat* (Washington DC: Brookings Institution, 1985).

SAC's Looking Glass airborne command post is no longer kept constantly airborne but it is flown at unpredictable intervals and therefore may not be reliably targeted, however, its home base can be. The Navy's TACAMO aircraft for submarine communications also have been taken off continuous airborne alert.

38. Seventy-five is the notional number of US bomber dispersal bases used in Alton H. Quanbeck and Archie L. Wood, *Modernizing the Strategic Bomber Force* (Washington DC: Brookings Institution, 1976), p.51. Carter, "Assessing Command System Vulnerability," p.566, cites a total of 58 SAC bomber and tanker bases, SAC dispersal bases, and SAC secondary dispersal bases. The number of CIS dispersal bases may be considerably fewer. One estimate of the number of CIS bomber bases, which counted CIS long-range, intermediate-range, and medium-range bomber bases, as well as arctic staging bases, was 24. Barbara G. Levi, Frank N. von Hippel, and William H. Daugherty, "Civilian Casualties from 'Limited' Nuclear Attacks on the Soviet Union," *International Security* **12**, 3, Winter 1987/88, pp.168–189.

In a severe crisis, part of the bomber forces conceivably could be put on airborne alert, and these planes would essentially be immune from cruise missile attack.

39. David Holloway and Condoleezza Rice, "The Evolution of Soviet Forces, Strategy, and Command," in Kurt Gottfried and Bruce Blair, eds., *Crisis Stability and Nuclear War* (New York: Oxford University Press, 1988) p.144; Rose E. Gottemoeller, *Land-Attack Cruise Missiles*, Adelphi Papers No. 226 (London: International Institute for Strategic Studies, 1987/88) p.23.

40. Similarly, even though Soviet Yankee ballistic missile submarines are used to patrol relatively close to US coasts simply because of the short range of their missiles, they nonetheless raised concern about reduced-warning attacks.

41. George N. Lewis and Theodore A. Postol, "Possible Responses."

Appendix A: The Range of a Tomahawk-like Cruise Missile

In this appendix the range of a Tomahawk-like cruise missile is estimated and the potential for future range increases is evaluated. Table A-1 lists some of the relevant Tomahawk physical characteristics assumed in our calculations.

For level cruise flight, the range R of an aircraft is given by the Breguet equation:[1]

$$R = \frac{V}{c}\frac{L}{D}\ln\left(\frac{W_i}{W_f}\right) = \frac{V}{c}\frac{C_L}{C_D}\ln\left(\frac{W_i}{W_f}\right) \tag{A-1}$$

where:

V = aircraft velocity
c = specific fuel consumption
L/D = lift-to-drag ratio
W_i = initial weight of aircraft
W_f = final weight of aircraft
C_L = aircraft coefficient of lift
C_D = aircraft coefficient of drag.

Because L/D will vary as fuel is consumed, an average value of L/D must be used, or the range computation must be broken into a series of constant L/D steps. Evaluating the range of a Tomahawk-like cruise missile thus requires a knowledge of its lift and drag characteristics as well as its engine's fuel consumption. We consider each of these in turn.

Lift and Drag Characteristics

The lift and drag generated by an aircraft can be written as:

$$L = \frac{\rho V^2 C_L S_{\text{ref}}}{2} \quad \text{and} \quad D = \frac{\rho V^2 C_D S_{\text{ref}}}{2} \tag{A-2}$$

where:

ρ = air density
S_{ref} = a reference area (usually the wing area).

For level cruise flight, an aircraft's lift must be equal to its weight; thus for a given aircraft altitude (which fixes ρ) and speed, the required value of C_L can be calculated.

Estimating C_D is more complex. For flight at speeds slow enough so that compressibility effects can be neglected, the drag coefficient can be written as:

$$C_D = C_{DP} + \frac{C_L^2}{e \cdot AR \cdot \pi} \tag{A-3}$$

where:

C_{DP} = parasite drag (the drag at zero lift)
e = airplane efficiency factor or Oswald efficiency factor; this is a correction factor to account for the deviation of the aircraft wing from an ideal wing
AR = aspect ratio (ratio of wing span to mean chord); AR = 6 for the Tomahawk.

Table A-1: Aerodynamic characteristics of the nuclear Tomahawk[a]

Weight	1184 kilograms
Diameter	0.52 meters
Length	5.55 meters
Fuselage wetted area	9.12 m^2
Wingspan	2.59 meters
Wing mean chord	0.43 meters
Wind aspect ratio	6.0
Wing reference area	1.11 m^2
Wing thickness/chord	0.082
Tail wetted area (all four fins)	0.84 m^2
Tail thickness/chord	0.083
Fuel weight[b]	513 kilograms

[a] E.C. Rooney and R.E. Craig, "Development of Techniques and Correlation of Results To Accurately Establish the Lift/Drag Characteristics of an Air Breathing Missile from Analytical Predictions, Sub-Scale and Full-Scale Wind Tunnel Tests and Flight Tests," in *Performance Prediction Methods*, AGARD Conference Proceedings No. 242 (Neuilly-Sur-Seine, France: Advisory Group for Aerospace Research and Development, 1977), pp.16.1–16.18; General Dynamics Company, "Cruise Missile Mass Properties Summary," GDC-AUR-89-052, March 1989.

[b] The fuel weight estimate is based on the assumption that the conventionally armed Tomahawk (BGM-109C) carries 272 kilograms (600 pounds) of usable fuel. General Dynamics Company, *A New Dimension In Conventional Airpower: Medium-Range Air-to-Surface Missile*, no date. The weight discrepancy between the conventional and nuclear Tomahawks (1,293 kilograms (2,849 pounds) conventional, 1,184 kilograms (2,607 pounds) nuclear) is assumed to be due to only three factors: warhead weight (450 kilograms (992 pounds) for conventional, 123 kilograms (270 pounds) nuclear), guidance weight (95 kilograms (210 pounds) conventional, 45 kilograms (100 pounds) nuclear), and fuel weight. These weights are from Kosta Tsipis, "Cruise Missiles," *Scientific American* **236**, 2, February 1977, pp.20–29. This gives an additional fuel weight of 268 kilograms (591 pounds). Assuming that 90 percent of this is usable fuel (the rest being unusable fuel, gas tanks, tubing, etc.), then the usable fuel weight for the nuclear Tomahawk of is roughly 513 kilograms (1,130 pounds).

This gives the nuclear Tomahawk an empty to full fuel-load weight ratio of 0.57. For comparison, the ratio for the ALCM-B is 0.58 (John C. Toomay, "Technical Characteristics," in Richard K. Betts, ed., *Cruise Missiles: Technology, Strategy, Politics* (Washington DC: Brookings, 1981), pp.31–52.

This expression relating an aircraft's lift and drag coefficients is known as a drag polar. The first term of C_D is known as the parasite drag, and accounts for drag that does not generate lift. For subsonic aircraft, most of this drag is due to skin friction and can be estimated for each major aircraft component (such as the fuselage, wing, and tail fins) and then summed.[2] The second term in the expression for C_D is known as the "induced drag" or the "drag due to lift" and accounts for the drag produced as a result of the lift generated by the wing (and also for other drag sources that varies as $C_L{}^2$).

The relatively simple geometric shape of the Tomahawk makes it possible to estimate these parameters following the procedures laid out in a number of aircraft design textbooks.[3] We obtain

$$C_D = 0.034 + 0.071 C_L^2 \qquad \text{(A-4)}$$

Figure A-1 compares our drag polar result with a published drag polar for the AGM-109 cruise missile. The AGM-109 was the air-launched version of the Tomahawk that was the losing candidate in the flyoff for the US Air Force's ALCM-B program. It is 21 inches longer than the naval Tomahawk, but its lift and drag characteristics reportedly are very similar.[4] As figure A-1 illustrates, our Tomahawk drag polar estimate is similar to the AGM-109 drag polar, except for a slightly greater parasite drag (thus our model will produce a slightly lower range than would be obtained using the AGM-109 drag polar), in the low C_L regime in which our estimate is valid.[5]

The Tomahawk Engine and Specific Fuel Consumption

The Tomahawk engine is the Williams Research Corporation's F-107-WR-400 turbofan, which along with the very similar F107-WR-101, developed for the US Air Force's ALCM-B, was derived from Williams' original small turbofan, the WR-19.[6] The development of these engines has taken place via a series of improvements and upgrades that is still ongoing. The F-107-WR-101 engine weighs 145 pounds and produces a maximum thrust of 635 pounds at sea level.[7]

The key engine parameter for range is the specific fuel consumption (SFC). The SFC is a measure of the amount of fuel the engine requires to produce a given amount of thrust and is usually expressed in units of pounds of fuel consumed per hour per

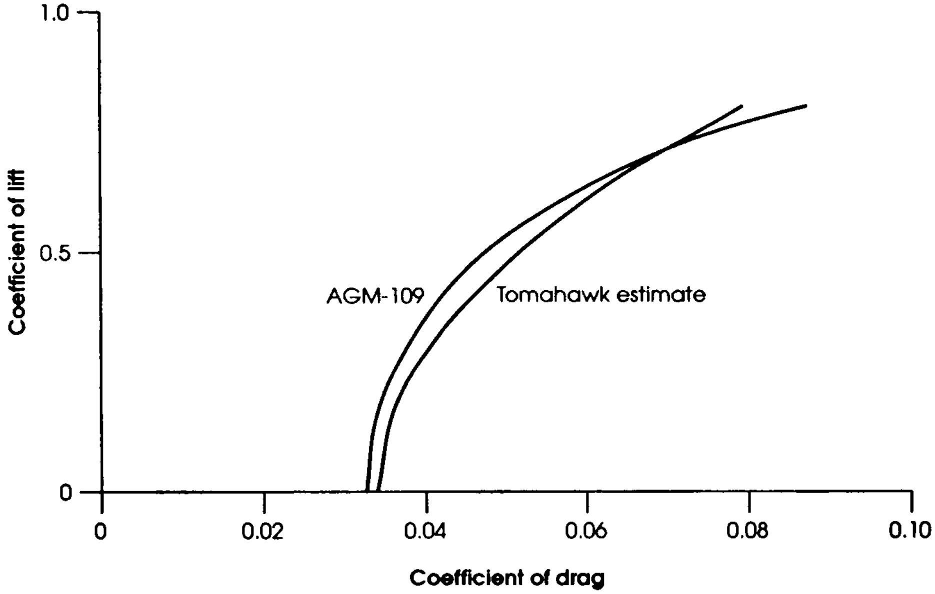


Figure A-1: Comparison of our estimated drag polar for a Tomahawk with published curve for the AGM-109 cruise missile. The curve for the AGM-109 is from B.J. Kuchta, "Technology Advances in Cruise Missiles," AIAA Paper No. 81-0937, *AIAA 1981 Annual Meeting and Technical Display—Frontiers of Achievement* (Long Beach, California: 12–14 May 1981).

pound of thrust (hr^{-1}). Most discussions of the Tomahawk put its SFC at about 1.0 hr^{-1},[8] although some estimates are as low as 0.7 hr^{-1}.[9] As we shall see, these numbers are not necessarily inconsistent with each other.

According to its manufacturer, the F107-WR-101 engine has a sea-level static SFC of 0.686 hr^{-1}.[10] This figure is not directly applicable to a Tomahawk in flight because it is a test stand value, with the engine at rest relative to the air around it. The specific fuel consumption of a turbofan engine increases with velocity, with the effect being more pronounced in engines with higher bypass ratios.[11] In addition, there are also losses associated with the installation of the engine into the airframe; however, these losses are typically only a few percent for most aircraft.[12] The SFC for the Tomahawk engine under cruise flight conditions will therefore be greater than the static value; an increase in SFC of about 30–40 percent, giving a sea level cruise value of about 0.9–1.0 hr^{-1}, is a reasonable first approximation.

A better estimate of the variation of SFC with speed and altitude can be made by performing an ideal cycle analysis of a Tomahawk-like engine.[13] The resulting variation of SFC with Mach number for several different altitudes is shown in figure A-2.[14] In estimating the range of a Tomahawk-like missile, we will use the data shown in figure A-2, increased by 3 percent to take installation losses into account.

Maximum Range

We now have all of the information necessary to estimate the range of a Tomahawk-like missile flying at a constant speed and altitude, and results of this calculation are shown in table 2 of the main text.[15] However, maximum range is not obtained by flying at a constant altitude and speed. From the Breguet equation, it is clear that an aircraft's range will be maximized if the quantity $(V/c) \cdot (L/D)$ is maximized.

In estimating maximum range, a standard assumption is that the variation in specific fuel consumption with speed is small and can be neglected in determining the optimum flight speed.[16] If this assumption is made, it is straightforward to show that the maximum range is obtained when:[17]

$$C_L = \sqrt{\frac{C_{DP} \cdot \pi \cdot AR \cdot e}{3}} \qquad \text{(A-5)}$$

This result was used to produce figure A-3, which shows the optimal speed V_{best} for best range for a nuclear Tomahawk as a function of the fraction of its fuel expended.[18] Maximum range results obtained by using optimized velocities that vary with the missile weight are also included in table 2.

Several points should be borne in mind in considering these results. First, these calculations neglect the variation of the specific fuel consumption with speed in determining the optimum speed; including this effect would decrease the optimum speed and slightly increase the maximum range. Second, the SFC of a turbofan engine generally increases once its thrust is reduced below about 70 percent of maximum thrust. This is not accounted for in these calculations,[19] and would lead to a (probably small) range decrease. Finally, to achieve the actual best range, one would vary the flight altitude as well as speed.

Increasing the Range of a Tomahawk-like Cruise Missile

The range of a Tomahawk-like missile is constrained by the volume of fuel it can carry.[20] Thus the most straightforward way to increase the range of such a missile is to

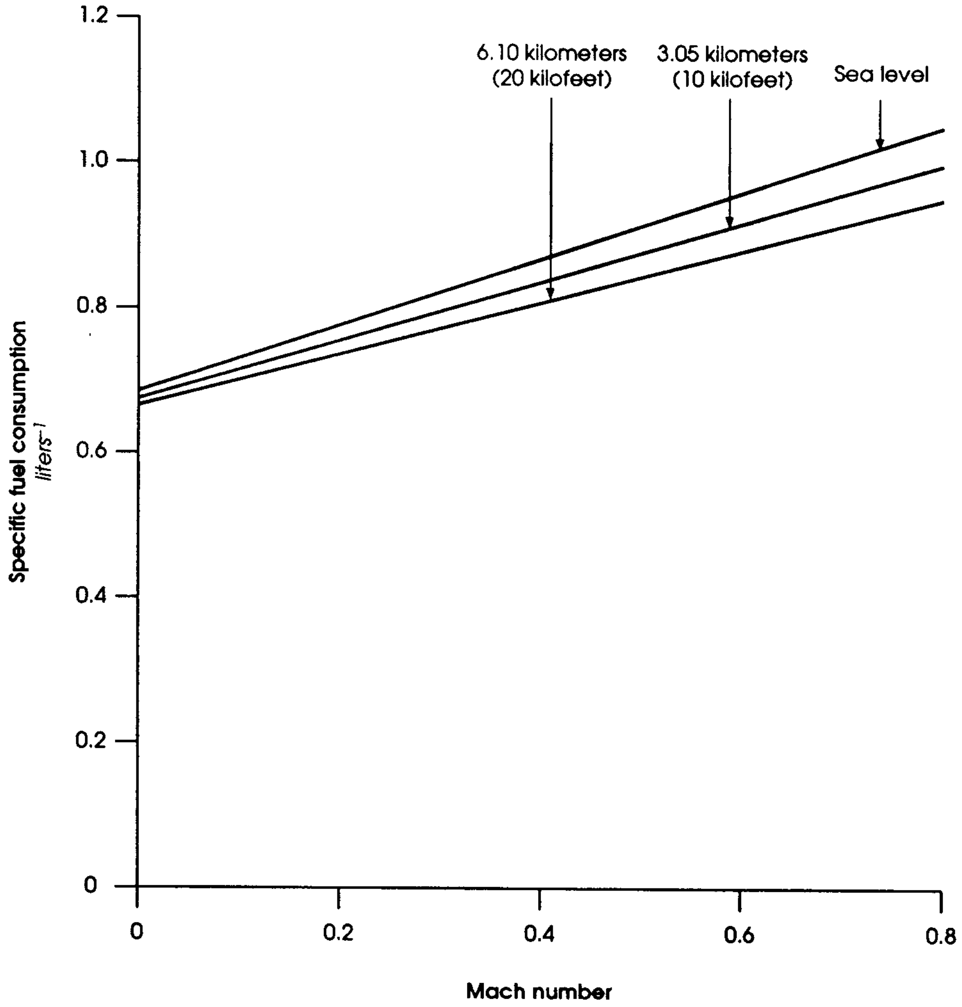


Figure A-2: Estimated variation of Tomahawk specific fuel consumption with missile speed.

increase its volume.[21] However, in many cases, the size of the missile will be constrained by other considerations, such as fitting existing launchers. In this discussion, we will assume that range improvements are constrained by the requirement that they do not result in an increase in missile volume.

Some of the factors that could increase cruise missile range are:

Lighter airframes (and other components)

New materials may allow the construction of much lighter airframes. To estimate the potential range gain associated with such a weight reduction, we assume that the airframe weight of the Tomahawk is reduced by one third.[22] In our aerodynamic model,

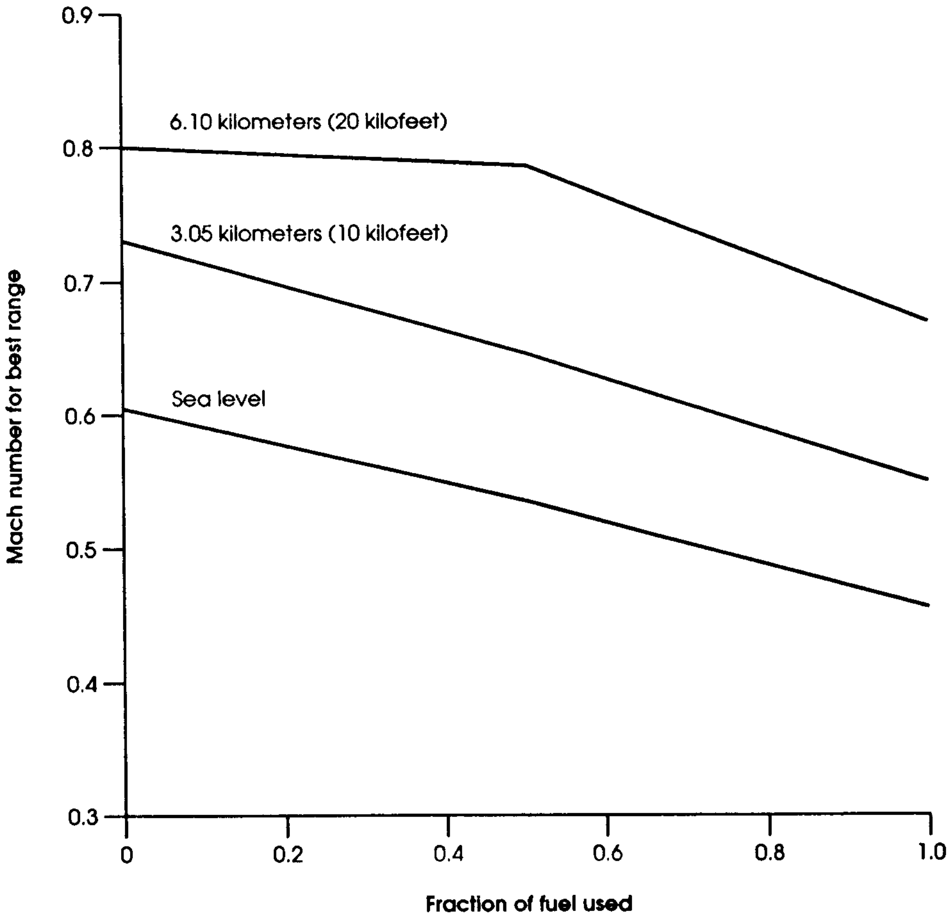


Figure A-3: Speed for best range (V_{best}) for the nuclear Tomahawk at three different altitudes as a function of fraction of fuel consumed. This optimization does not include the variation of specific fuel consumption with speed, so the actual optimum speeds will be slightly lower than those shown here.

this gives a range gain at sea level of 100 kilometers (an increase of 3.3 percent) at a constant speed of Mach 0.65, and a gain of 330 kilometers (an increase of 9.7 percent, giving a straight-line range of 3,730 kilometers) if the missile speed is optimized for best range. Thus a range gain of 10 percent or more appears possible if the missile airframe or other components can be lightened significantly, and greater increases could be possible if these changes allow the missile's fuel volume to be increased.[23]

Improved Aerodynamics

Range could be increased by improved aerodynamic design; for example, by using wings that produce greater lift, thereby improving the lift-to-drag ratio and allowing flight at lower speeds.[24] One proposal for a new Tomahawk wing would have increased its lift without increasing the wing size, thereby producing a 5–10 percent range increase.[25]

Guidance Improvements

Improvements in guidance technology can improve the operational range of a Tomahawk-like cruise missile by reducing the degree to which it needs to deviate from a straight-line course in order to use terrain maps. Improvements in the TERCOM system or the development of new sensors for other types of terrain map guidance systems could reduce the need for such course deviations by allowing more types of terrain to be used for maps. Use of GPS satellite guidance could completely eliminate guidance-driven course deviations:[26] however, due to its reliance on potentially vulnerable satellites, the use of GPS is unlikely to completely replace terrain-mapping, at least in strategic nuclear cruise missiles. The United States is planning to add GPS receivers to Block III conventionally armed land-attack Tomahawks; however, GPS will supplement rather than replace the current guidance system. The US Navy has stated that the use of GPS on conventional Tomahawks will increase their standoff range by up to 20 percent.[27]

Stealth Technology

The application of stealth technology to cruise missiles could potentially improve their operational range in at least two ways. First, by reducing the need for them to maneuver around defended areas, and second, by allowing them to fly a greater portion of their missions at high altitudes. Whether either approach will actually be useful in practice depends not only on the effectiveness of the stealth techniques, but on the level of sophistication of the sensors and defenses of the target country.

On the other hand, a requirement to add stealth features to a cruise missile could actually decrease its range by adding weight, by decreasing the volume available for fuel (due to shaping requirements or the need for thick radar absorbing materials), or by requiring a less-than-ideal aerodynamic design.

Improved Fuels

Since Tomahawk range is constrained by the volume of fuel it can carry, it is advantageous to use high-density fuels.[28] The Tomahawk fuel is RJ-4 (also known as TH-Dimer).[29] This fuel is 13 percent denser and has a 12 percent higher heating value per unit volume than the Navy's standard JP-5 fuel. The use of RJ-4 instead of JP-5 is said to have gained the Tomahawk 200 kilometers (125 miles) in range,[30] and more exotic fuels were said to have been capable of giving a 645 kilometer (400 mile) advantage over JP-5 but were rejected as being too dangerous if spilled.[31] There are a number of liquid fuels, such as RJ-5 (also known as Shelldyne-H), that are known to have higher energy densities than RJ-4 (RJ-5 has a heating value 15 percent greater than RJ-4 and 29 percent greater than JP-5).[32] There has also been interest in fuels consisting of boron or carbon suspended as a slurry in a high-energy base fuel, which could potentially produce very large improvements in energy density.[33] However, in the last few years interest appears to have shifted away from improved fuels and towards improved engine designs as a means of increasing cruise missile ranges.[34]

Engine Improvements

Improved engine SFC is potentially the most important source of cruise missile range increases. Incremental improvements to the Tomahawk engine have already occurred, and a planned upgrade to conventional land-attack Tomahawk cruise missiles will include an upgraded engine (the F107-WR-402) that decreases specific fuel consumption by 3 percent and increases maximum thrust by 19 percent.[35]

New engine designs may be able to produce much larger reductions in SFC. One study of advanced turbofan engines (bypass ratio = 3) and super high bypass ratio turbofans (bypass ratio = 10) for cruise missiles concluded that they could reduce SFC to below 0.8 and 0.7 respectively at Mach 0.65 and sea level.[36] A study of cruise missile engines based on technologies expected to be mature by the year 2000 concluded that an advanced turbofan could produce a 38 percent improvement in fuel efficiency.[37]

In recent years, propfan engines have increasingly been viewed as a potential means for obtaining much greater cruise missile ranges.[38] Propfans ultimately may be capable of producing improvements in SFC of up to 50 percent,[39] which could double cruise missile range.

It is clear that advanced small engines could greatly increase cruise missile range. How great of an increase will be possible is likely to depend on the degree to which the difficult problems (such as designing folding propfan blades) involved in packaging these engines into a small diameter cruise missile body can be solved, the degree to which these solutions are compatible with radar cross section requirements, and the degree to which range improvements are considered to justify the cost involved in developing and building such engines.

Conclusions on Cruise Missile Range

In recent years, interest in the United States appears to have centered primarily on producing a conventionally armed cruise missile with roughly twice the range of the current conventional Tomahawk.[40] Given the magnitude of the possible improvements discussed above, this appears to be feasible, although it might be difficult to achieve in a next generation missile.

Although current interest may be in conventionally armed missiles, the technology developed for such missiles is very likely to find its way into future nuclear cruise missiles. A 50 percent increase over current nuclear cruise missile ranges could produce missiles with operational ranges of 4,500 kilometers and much greater maximum ranges.[41]

Such a range increase could greatly increase the surprise attack threat posed by cruise missiles. Bombers could launch ALCMs undetected from great standoff ranges. Similarly, submarines would no longer have to be close to US or CIS shores to strike deep within either country. Further, such a range increase would allow much more maneuvering in order to exploit gaps in air surveillance systems.

NOTES AND REFERENCES

1. This equation is derived in many texts, such as Richard S. Shevell, *Fundamentals of Flight,* 2nd edition (Englewood Cliffs, New Jersey: Prentice Hall, 1989) chapter 15.

2. The pressure drag due to each component can be accounted for by the use of empirically determined form factors. In addition, there are numerous other minor sources of drag that must be accounted for. These include drag due to the engine inlet, drag due to the interference between the flow fields of different components (interference drag), drag due to wing twist, drag produced by the tail fin lift needed to counter

the pitching moment of the wings (trim drag), and drag due to control surfaces. Most of these contributions are quite small and some of them are implicitly accounted for in the empirical expressions used to calculate the drag of the major components. Shevell suggests adding 6 percent to 10 percent to account for these sources, and we use the higher figure here. Shevell, *Fundamentals of Flight*, p.184.

3. The references used here were: Shevell, *Fundamentals of Flight*; Leland M. Nicolai, *Fundamentals of Aircraft Design* (San Jose, California: METS Inc., 1984); Daniel P. Raymer, *Aircraft Design: A Conceptual Approach* (Washington DC: American Institute of Aeronautics and Astronautics, 1989); Jan Roskam, *Airplane Design, Part VI: Preliminary Calculation of Aerodynamic, Thrust, and Power Characteristics* (Ottawa, Kansas: Roskam Aviation and Engineering Corporation, 1987); and Egbert Torenbeek, *Synthesis of Subsonic Airplane Design* (Boston, Massachusetts: Kluwer Academic Publishers, 1982).

4. R.E. Craig and R.J. Reich, "Flight Test Aerodynamic Drag Characteristics Development and Assessment of Inflight Propulsion Analysis Methods for AGM-109 Cruise Missile," AIAA Paper No. 81-2423, *AIAA/SETP/SFTE/SAE/ITEA/IEEE 1st Flight Testing Conference,* Las Vegas, Nevada, 11–13 November 1981, table 3 and figures 23 and 24.

5. Our drag polar is also in general agreement with a drag polar (C_D = 0.03 + $0.07C_L^2$) for a "typical wing-body cruise missile;" see Leland M. Nicolai, "A Perspective on the Requirements for Advanced Cruise Missiles," AIAA Paper No. 79-1817, *AIAA Aircraft Systems and Technology Meeting,* New York, 20–22 August 1979. Although Nicolai's drag polar is not said to be associated with any particular missile, the missile drawing used to illustrate the wing-body type of cruise missile in Nicolai's paper is a Tomahawk. Nicolai's drag polar is at Mach 0.7, whereas our estimate is at M = 0.65, but the drag polar has only a very weak dependence on Mach number in this Mach number range.

6. These engines and their development are described in: T.K. Wills and E.P. Wise, "Development of a New Class of Engine—The Small Turbofan," AIAA Paper No. 76-618, *AIAA/SAE 12th Propulsion Conference*, Palo Alto, California, 26–29 July 1976; and L. Cruzen, "Cruise Missile Propulsion Versus Commercial Airliner Propulsion—Different Challenges Can Produce Similar Engine Cycles," AIAA Paper No. 83-1176, *AIAA/SAE/ASME 19th Joint Propulsion Conference*, Seattle, Washington, 27–29 June 1983.

The Tomahawk engine is very similar to that of the ALCM-B, "differing only in accessory system location and tailpipe design to satisfy installation requirements" (Wills and Wise, "Development of a New Class of Engine," p.15). These differences are due in large part to the different location of the engine inlet on these missiles.

7. Cruzen, "Cruise Missile Propulsion," table 1.

8. Kosta Tsipis, "Cruise Missiles," *Scientific American* **236**, 2, February 1977, pp.20–29; John C. Toomay, "Technical Characteristics," in Richard K. Betts, ed., *Cruise Missiles: Technology, Strategy, Politics* (Washington DC: Brookings, 1981) pp.31–52.

9. Doug Richardson, "The Cruise Missile," *Flight International* **112**, 3577, October 1977, pp.963–968.

10. Cruzen, "Cruise Missile Propulsion," p.3.

11. See Shevell, "Fundamental of Flight," pp.344–345, and Raymer, "Aircraft Design," pp.17–18. The F107-WR-101 has a relatively low bypass ratio of 1.00 (Cruzen, "Cruise

Missile Propulsion," table 2). In a turbofan engine, part of the energy produced by the jet engine core (a turbojet) is used to drive a low pressure fan. Thus a larger mass of air is accelerated to a lower speed than in a pure turbojet, resulting in greater efficiency. The ratio of the mass of air bypassing the turbojet core to that passing through it is known as the bypass ratio. In general, the higher the bypass ratio is, the more fuel efficient the engine will be.

12. The design of the Tomahawk, in which the fuel capacity is volume limited, involved trade-offs concerning the engine inlet design. "General Dynamics settled on a deployable scoop for good engine fuel consumption and no boundary layer ingestion with moderate concessions in fuel volume, drag, and mechanical complexity." Richard DeMeis, "Designing a Cruise Missile: General Dynamics' BGM-109 Tomahawk," *Aerospace America* **23**, 1, January 1985, pp.110–114.

13. This analysis was done by Jerry Sheehan (then at the Defense and Arms Control Studies Program at MIT, now at the US Congressional Office of Technology Assessment), using the computer programs ONX and OFFX developed by Jack D. Mattingly. Jack D. Mattingly, *On-Design and Off-Design Aircraft Engine Cycle Analysis Computer Programs: ONX and OFFX User Guide* (Washington DC: American Institute of Aeronautics and Astronautics, 1990). These programs were developed for use with the book Jack D. Mattingly, William H. Heiser, and Daniel H. Daley, *Aircraft Engine Design* (Washington DC: American Institute of Aeronautics and Astronautics, 1987).

14. In order to get the engine cycle analysis program to converge at all speeds and altitudes, it was necessary to use a bypass ratio 40 percent higher than the actual engine value of 1.00. This will lead to an overestimate of the SFC variation with speed (and therefore to an underestimate of the cruise missile range) by a few percent at higher speeds.

15. In this computation, the flight was broken up into 1,130 increments in each of which 1 pound (0.45 kilograms) of fuel was consumed.

16. Shevell, *Fundamentals of Flight*, chapter 15, and Raymer, *Aircraft Design*, chapter 17.

17. Shevell, *Fundamentals of Flight*, p.278.

18. The derivation of V_{best} also assumes that the speed is low enough so that no supersonic wave drag occurs. This assumption breaks down for speeds greater than Mach 0.76. In situations where V_{best} would be greater than Mach 0.76, a new value of V_{best} was computed taking the wave drag into account.

19. Willis and Wise show data on variation of SFC with thrust for the Tomahawk engine. At sea level, this shows a 10 percent rise in SFC when the thrust is reduced to about 50 percent of an (unspecified) intermediate power level. Willis and Wise, "Development of a New Class of Engine," p.14.

20. Submarine-launched conventional land-attack Tomahawks were originally weight limited. In order for their rocket booster to get them out of the water and up to cruise speed from normal launch depths, their weight had to be reduced by off-loading some fuel. This problem is being corrected by the use of a more powerful rocket booster.

21. An increased fuel load may be responsible for much of the range increase achieved in the Advanced Cruise Missile, which appears to have a substantially larger volume than the ALCM-B.

22. Tsipis gives an airframe weight of 364 kilograms (800 pounds) for the Tomahawk

(Tsipis, "Cruise Missiles," p.22). A one third reduction in this figure would therefore reduce the missile weight from 1,185 kilograms (2,607 pounds) to 1,064 kilograms (2,340 pounds). Since the amount of fuel the Tomahawk carries is constrained by volume rather than weight limitations, this lost weight will not necessarily simply be replaced by fuel. In making this estimate, we assume the fuel weight does not change.

23. Block III conventional Tomahawks will have a smaller, lighter (by 250 pounds) warhead that will allow more fuel to be carried. Together with a 3 percent reduction in SFC provided by an improved engine, these changes are said to provide a range increase from 1,300 kilometers to 1,670 kilometers, a 29 percent increase. Stanley W. Kandebo, "US Fires Over 25 Percent of its Conventional Land Attack Tomahawks in First Week of War," *Aviation Week and Space Technology* **134**, 4, 28 January 1991, pp.29–30.

24. The original Tomahawk design had two different wing designs, one for versions that emphasized maneuverability and one for versions which emphasized range; eventually it was decided to use the wing which emphasized maneuverability on all of the Tomahawks. E.C. Rooney and R.F. Lauer, "Correlation of Full Scale Wind Tunnel and Flight Measured Aerodynamic Drag," AIAA Paper 77-996, *AIAA/SAE 13th Propulsion Conference,* Orlando, Florida, 11–13 July 1977, p.7.

25. Kuchta, "Technology Advances in Cruise Missiles," pp.4–6.

26. A GPS-only guidance system would also almost certainly be smaller and lighter than a TERCOM system.

27. Statement of Rear Admiral William C. Bowes (director, Cruise Missiles Project), before the Defense Subcommittee of the House Appropriations Committee, 21 April, 1988, p.11. Admiral Bowes stated that GPS "increases standoff range up to 20 percent." It is possible that some or all of this standoff range increase is due to limits imposed on standoff range by the size of the landfall TERCOM map. However, an illustration that accompanies the statement strongly suggests that this standoff range increase is due to the elimination of the need for course deviations to overfly TERCOM mapped areas. This suggests that this factor is responsible for a large part of the difference between operational and straight-line ranges.

28. C.L. Brackett and R.L. Trauth, "Small Turbine Engine Experience with High Density Fuels," AIAA Paper No. 83-1177, *AIAA/SAE/ASME 19th Joint Propulsion Conference,* Seattle, Washington, 27–29 June 1983; G.W. Burdette, H.R. Lander, and J.R. McCoy, "High Energy Fuels for Cruise Missiles," AIAA Paper No. 78-267, *AIAA 16th Aerospace Sciences Meeting,* Huntsville, Alabama, 16–18 January 1978; "Fuel Research Spurred by Cruise Missiles," *Aviation Week and Space Technology* **104**, 4, 26 January 1976, pp.111–113.

29. The ALCM-B does not use this fuel because its low freezing temperature, high low-temperature viscosity, and low volatility make it unsuitable for use in the very cold environment that would often be involved in strategic bomber operations. The ALCM-B uses a high-energy fuel known as JP-9, which has mass and energy densities similar to RJ-4.

30. DeMeis, "Designing a Cruise Missile." It is unclear to what variant of the Tomahawk this statement applies. However, since a 200 kilometer increase in the range of the conventional land attack (from 1,100 kilometers to 1,300 kilometers) represents an 18 percent increase, whereas for the nuclear Tomahawk (2,300 kilometers to 2,500 kilometers) it is an 8.7 percent increase, it appears likely that this statement applies to the nuclear version. The use of RJ-4 actually decreases the SFC relative to JP-5

because it has less energy per unit weight. However, RJ-4 is denser, and therefore has more energy per unit volume. Since the Tomahawk's fuel capacity is volume limited, not weight limited, it pays to use a denser fuel.

31. DeMeis, "Designing a Cruise Missile," p.112.

32. This may have been the fuel mentioned as having been rejected as being too dangerous in the preceding sentence, since RJ-5 was apparently given serious consideration for use in the Tomahawk and is derived from an insecticide.

33. Boron slurry could have a heating value 88 percent greater than RJ-4 (although it is said to leave an undesirable exhaust residue). However, even though carbon slurry has a smaller heating value (heating value 27 percent greater than RJ-4) it is said to appear more promising than boron slurry. Nicolai, "A Perspective on the Requirements," p.3.

34. Bill Sweetman and Brian Wanstall, "Missile Propulsion Options Increase," *Interavia* **44**, 8, September 1989, pp.912–916.

35. This new engine is to be used in conventional land-attack Tomahawks constructed under the Block III improvement program, due to begin in fiscal year 1991. Norman Friedman, *World Naval Weapons Systems 1991/92* (Annapolis, Maryland: US Naval Institute Press, 1991), p.122.

36. W. Douglas Hoy, "Long-Range Subsonic Cruise Missile Propulsion Performance Design," AIAA Paper No. 89-2474, *AIAA/ASME/SAE/ASEE 25th Joint Propulsion Conference,* Monterey, California, 10–12 July 1989.

37. R. Pampreen, "Engine Studies for Future Subsonic Cruise Missiles," AIAA Paper No. 86-1547, *AIAA/ASME/SAE/ASEE 22nd Joint Propulsion Conference,* 16–18 June 1986, Huntsville, Alabama. This paper also concluded that a recuperative turbofan could improve the SFC by up to an additional 13 percent, but that this improvement was canceled out by lost fuel volume due to the larger size of the engine.

38. Breck W. Henderson, "Propfan Engine May Be Suitable for Next Generation Cruise Missile," *Aviation Week and Space Technology* **136**, 1, 6 January 1992, pp.62–63; Sweetman and Wanstall, "Missile Propulsion Options Increase," p.913. A propfan is basically an unducted turbofan, where the fan blades are on the outside of the engine cowling, thereby in effect achieving very high bypass ratios.

39. "Boeing Studies Long-Range Propfan-Powered ALCM," *Aviation Week and Space Technology* **129**, 8, 22 August 1988; Hoy, "Long-Range Subsonic Missile Propulsion," p.2; Sweetman and Wanstall, "Missile Propulsion Options Increase," p.913.

40. However, with the cancellation of the Long-Range Conventional Cruise Missile Program, the US does not appear to have an ongoing program to develop such a missile.

41. Because such missiles are likely to be launched at large standoff ranges, they may be able to fly a substantial part of their mission at high altitudes, which would substantially increase their operational range. Also note that such ranges could make possible the deployment of a long-range ground-launched cruise missile, which would not be limited by the INF treaty if its range exceeded 5,500 kilometers.

Appendix B: Over-the-horizon (OTH) Radars And Cruise Missile Detection

This appendix will assess the OTH-B radar system's cruise missile detection capabilities and will briefly consider the prospects for improved future OTH systems.

OTH radars overcome the limits of line-of-sight detection by exploiting reflection by ionospheric electrons to "bounce" radar energy off the ionosphere to targets far beyond the horizon. Some of the radar energy scattered off the target then returns to the radar via the same ionospheric reflection mechanism.[1]

The effectiveness of an ionospheric layer in reflecting a radar wave depends on the frequency of the radar wave and its angle of incidence to the ionospheric layer, and on the electron density of the layer. The greater the electron density or angle of incidence, the higher the frequency of the radar wave that can be reflected. The frequencies at which OTH radars can operate are determined by the nature of the ionosphere and lie in the HF frequency band from 3 to 30 megahertz.

While the ionosphere is an extremely dynamic and complex environment, some generalizations about its nature can be made. Because the ionospheric electrons are primarily due to solar activity, electron densities are much higher during the day than at night. Thus OTH radars will generally operate at higher frequencies during the day than at night. Similarly, the ionospheric electron density, and therefore the frequencies which can be used, will also be higher during periods of high solar activity (for example, during the peak of the 11 year solar cycle). The characteristics of the ionosphere also vary with the seasons and with the location of the radar as well as the direction in which it is looking. OTH operation is generally not possible when looking into areas of auroral activity, such as over the north magnetic pole.[2]

Other important OTH parameters, such as propagation losses and noise levels, also undergo large variations with season, time of day, solar activity, radar location and orientation, and other factors. OTH radars can suffer significant propagation losses due to ionospheric absorption. This absorption will generally be higher during the day than at night. Unlike radars operating at higher frequencies, the primary noise sources for OTH radars are external ones, such as cosmic noise, man-made interference, and lightning. Noise from lightning and other atmospheric effects tends to be greater at lower frequencies, at night, and during the summer.

The constantly changing nature of the ionosphere requires that it be continually monitored so that the OTH operating parameters can be adjusted to suit the changing conditions. The operating frequency must be adjusted not only to obtain propagation to a specified range, but also to avoid frequencies being used by other users.[3] Even with such adjustments, there will be times when the ionosphere is too disturbed to permit operation.[4]

Maximum detection ranges of about 4,000 kilometers are possible with a single bounce off the ionosphere; however, in actual practice, the maximum achievable range is usually limited to about 3,300 kilometers. Longer ranges are possible by employing multiple bounces off the ionosphere, however, this approach is unlikely to be useful for detecting low RCS targets and will not be considered here. In addition, OTH radars generally have a minimum detection range as well, which can vary from about 500 to more than 1,000 kilometers.[5]

The long wavelengths (10–60 meters) used by OTH radars require very large antennas if reasonably narrow beam widths are to be obtained, and the long detection ranges require very high average powers, typically, 0.1–1 megawatts. Thus OTH radars tend to be very large facilities which are expensive to construct.[6] However, they compensate for this by being able to cover enormous amounts of territory, typically 4 to 5 million km^2 for a single 60°-wide surveillance sector.[7] Other than space-based radars, no other type of radar can provide coverage of such broad areas.

The United States currently has two major OTH programs under way, the Air Force's OTH-B system and the Navy's relocatable OTH radar (ROTHR) system.[8] We will focus on the Air Force system, since it is a more powerful system intended for strategic surveillance of the US perimeter, whereas the Navy system is intended primarily for tactical missions.[9] The $2.6 billion OTH-B system was to be deployed at four sites: on the east coast in Maine, on the west coast near the California–Oregon border, in the central United States (facing south), and in Alaska. Several radars were to be at each site, each covering a different 60°- wide sector, giving a total of 12 sectors.[10] As of early 1991, the east coast site was operational and the west coast site was nearing completion,[11] although as discussed in the main text, it now appears unlikely that the system will ever be completed.

Some of the parameters of the US OTH-B system are listed in table B-1. Each OTH-B sector has a separate receive and transmit antenna, typically separated by about 100–200 kilometers. Each transmit antenna actually comprises six separate antennas, each transmitting over a different band of frequencies, with a total length of about 1,110 meters (3,630 feet). The effective radiated power (the product of the average power and the transmit gain[12]) is "up to 10^8 watts."[13] The azimuth transmit beamwidth is about 7.5°. The receive antenna for the east coast system is about 1,520 meters (5,000 feet) in length, and is used to form four simultaneous overlapping receive beams, each 2.75° wide. Together these receive beams cover a total azimuth of 7.5° and an area up to 925 kilometers in depth. The total surveillance area of each sector, covering 60° in azimuth and ranges of between 925 and 3,330 kilometers, is then covered by stepping the beam sequentially. Thus a total of about 24 steps would be required to scan the entire surveillance area once.[14]

OTH radars illuminate very large areas of the earth's surface, resulting in large clutter backgrounds that must be rejected in order to detect targets. As with the other types of radars, this is done by Doppler processing. However, since the low radar frequencies result in small Doppler shifts,[15] integration times much longer that those typically used for line-of-sight radars are required.[16] Typical integration times for aircraft are of the order of 1–10 seconds.[17]

A long coherent integration time is also desirable in order to increase the signal-to-noise ratio (S/N). However, long integration times lead to low search rates. Assuming that 24 steps are required to cover an entire OTH surveillance sector, then an integration time of 1 second leads to a scan time of 24 seconds, and an integration time of 10 seconds to a scan time of 4 minutes.

We can make a simple estimate of the ability of the OTH-B system to detect cruise missiles by using the OTH radar equation. This calculation also serves to illustrate some of the differences between OTH and other, more familiar, types of radars. The OTH radar equation can be written as:

$$\frac{S}{N} = \frac{P G_t G_r t \lambda^2 \sigma}{(4\pi)^3 R^4 (kT) N L_P L_S} \qquad \text{(B-1)}$$

where:

P = average power
G_t = transmit gain
G_r = receive gain
t = integration time
λ = radar wavelength

Table B-1: US AN/FPS-118 OTH-B system[a]

Frequency range	5–28 megahertz
Minimum range	925 kilometers
Maximum range	3,330 kilometers
Range segment length	925 kilometers
Azimuth coverage	60° per sector
Transmit antenna length	1,106 meters
Six separate antennas	Band A : 5.0 – 6.74 megahertz Band B : 6.74– 9.09 megahertz Band C : 9.09–12.25 megahertz Band D : 12.25–16.50 megahertz Band E : 16.50–22.25 megahertz Band F : 22.25–22.25 megahertz
Transmit power	1 MW (12 100 kilowatt transmitters)
Effective radiated power	up to 10^8 watts
Transmit azimuth beamwidth	7.5°
Waveform	Continuous wave/frequency modulated
Waveform repetition frequencies	20, 30, 45, 60 hertz
Waveform bandwidths	2.5, 5, 10, 50, 100 hertz
Receive antenna length	1,518 meters (east coast)
Receive beamwidth (east coast)	2.75° (four parallel, covering 7.5°)

[a] Kenneth J. Stein, "Backscatter Radar Unit Enters Production Phase," *Aviation Week and Space Technology* **177** 7, 16 August 1982, pp 68–77; Chris Bulloch, "Beyond the Far Horizon: USAF's Ionosphere Bouncing Radar Finally Ready To Go," *Interavia* **37**, 12, December 1982, pp.1302–1304; "New Radar Installations Promise 360-Degree Air Defense Perimeter," *Aviation Week and Space Technology* **123**, 23, 9 December 1985, p.55; Ramon Lopez, "The USA Builds its OTH-B Radar Barrier," *Interavia*, **42**, 4, April, 1987, pp.334–335; General Electric Company, "OTH-B ERS," no date.

σ = target radar cross section
R = target range
kT = Boltzmann's constant times room temperature
N = noise due to environment (in units of kT)
L_P = propagation losses
L_S = system losses.

Some of the parameters appearing in this equation are characteristics of the radar itself and are known or can be estimated. We will take the effective radiated power, PG_t, to be 10^8 W (= 80 decibels re 1 W)[18] and the receive gain to be 30 decibels.[19] It has been said that it is generally not cost-effective to attempt to reduce the system losses of an OTH radar below about 10 decibels;[20] we will optimistically take $L_S = 7$ decibels.

The integration time t is also (within limits set by the ionosphere) under the control of the radar operator. An integration time of about 1 second is typical when searching for targets such as large airplanes, and we will use this in estimating the performance of the radar against a bomber target. For low RCS targets such as cruise missiles, a longer integration time may be needed, and we will use $t = 10$ seconds in evaluating the detection performance against cruise missiles. Longer integration times could be used at the penalty of reduced search rates (thus probably requiring a higher probability of detection) or areas, or if there were information indicating the possible presence of a target in a given area.

We will consider two targets, a Tomahawk-like cruise missile[21] and a bomber-sized aircraft, both of which are assumed to be moving directly towards the radar. The RCS for both targets is frequency dependent, and the RCS versus frequency values used are illustrated in figure 3 of the main text.[22] For both targets, a multipath RCS enhancement of 6 decibels is also assumed to occur.[23]

The other radar equation parameters, such as wavelength, noise level, and propagation losses are not directly under the radar operator's control. For a given range, the ionospheric conditions will determine the required frequency. The propagation losses[24] and noise similarly depend not only on ionospheric conditions but also on the operating frequency. It is not possible to assign a single value or even a single functional dependence to each of these parameters, as they vary on a diurnal, seasonal, and solar cyclical basis, as well with the location and orientation of the radar.

Headrick[25] has compiled a set of charts that provide the operating wavelength, noise power, and propagation losses as a function of ground range for both day and night, and low and high solar activity, for each of four typical months (January, April, July, and October). These charts were used to determine λ, N, and R^4L_P as functions of ground range.

Substituting all of these factors into the OTH radar equation gives the results shown in figure 5 of the main text and in figure B-1, which shows the signal-to-noise ratio for a Tomahawk-like cruise missile for four different months, both day and night and for both low (sunspot number [SSN] = 10) and high (SSN = 100) levels of solar activity. A dashed line is drawn at S/N = 4 (6 decibels) as an estimate of the minimum S/N level required for detection by forming tracks.[26] This figure suggests that while the OTH-B system may be capable of detecting cruise missiles during the day, it appears to have little capability against them at night and in some circumstances falls short by more than two orders of magnitude.[27] This poor nighttime performance results from the lower frequencies that must be used at night.[28] These low frequencies result in a greatly decreased cruise missile RCS as well as in an increase in external noise.

We can also make a simple estimate of the clutter rejection requirements for cruise missile detection. Clutter is a potentially more serious problem for OTH than for line-of-sight radars because the degree of clutter rejection that will ultimately be possible may be limited by ionospheric effects rather than by equipment limitations. The OTH-B system has a maximum bandwidth of 100 kilohertz, corresponding to a range resolution of 1.5 kilometers.[29] Using an OTH-B receive beamwidth of 2.5° and considering detection over the sea (with an effective RCS clutter density[30] of −18 decibels), we obtain the signal-to-clutter ratios (S/C) shown in figure B-2 for the cruise missile and bomber targets for the month of October. Assuming that the signal must be 6 decibels greater than the clutter for detection, then clutter rejection capabilities of order 30–50 decibels are required for bomber detection and 55–85 decibels for cruise missile detection (see figure B-2). The clutter rejection requirements for bomber detection are

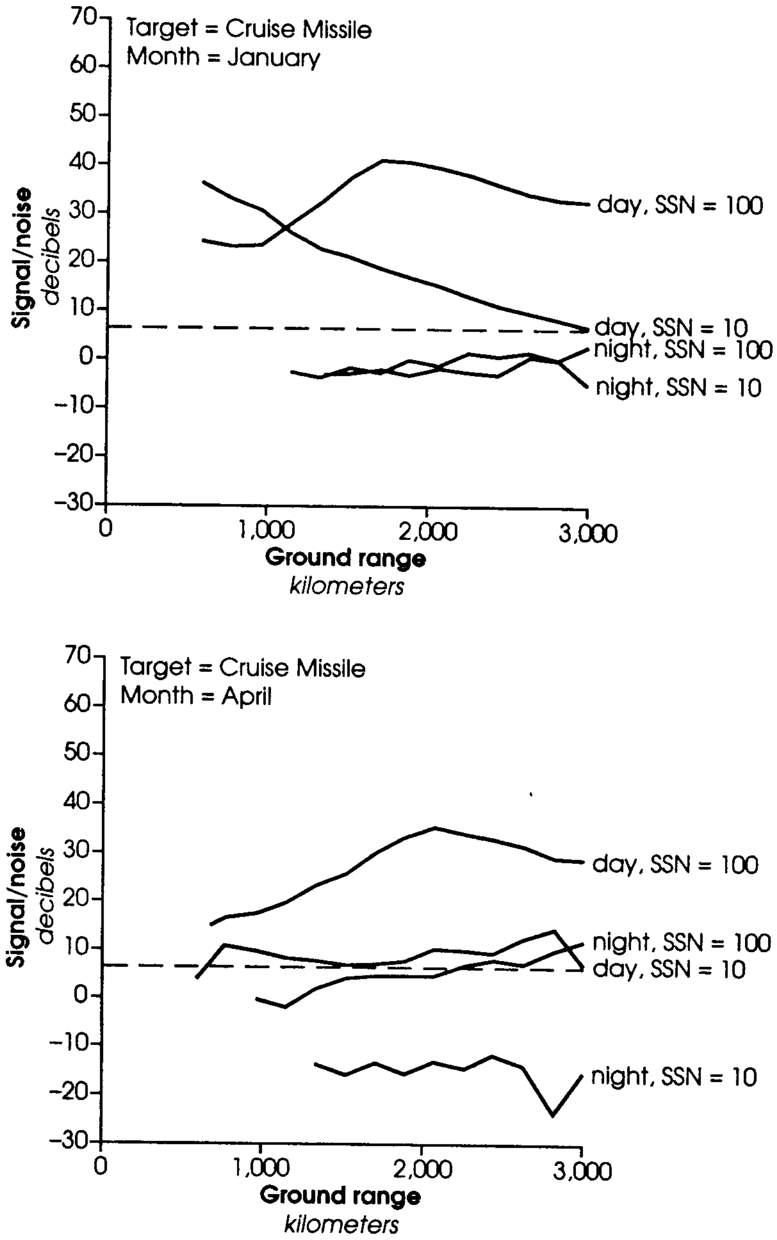
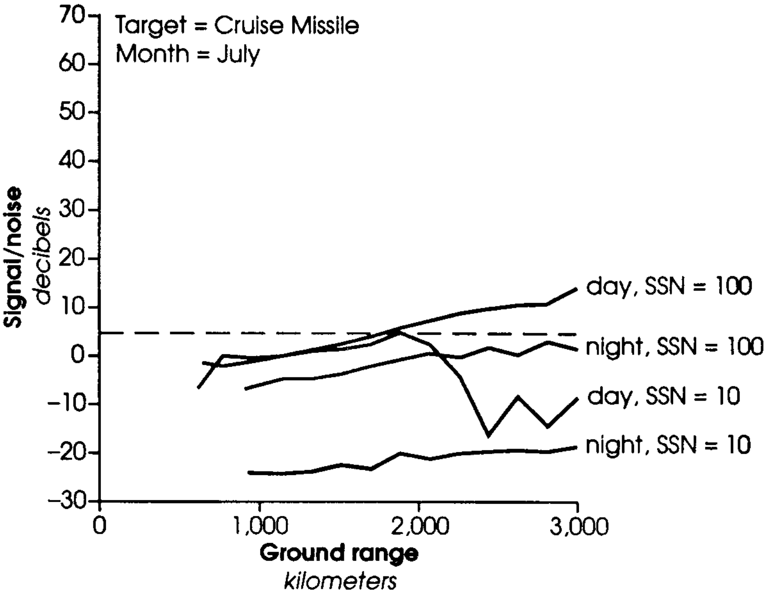
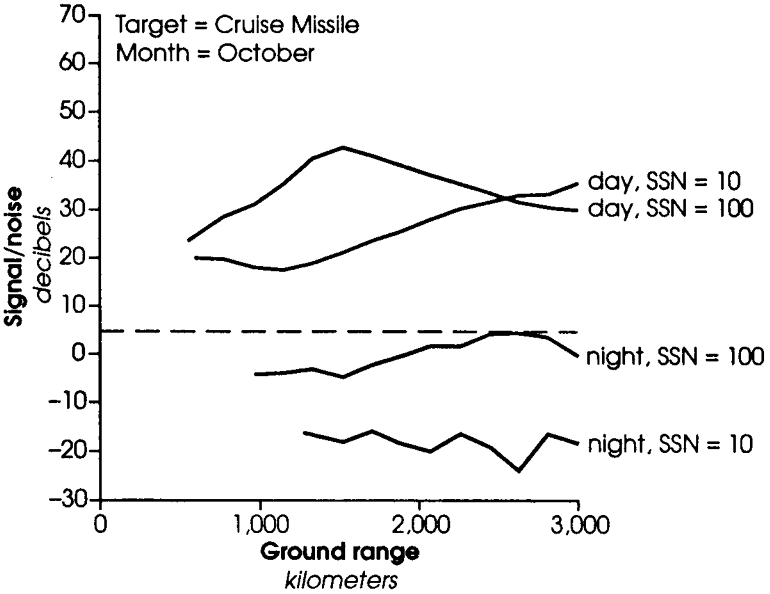


Figure B-1: OTH S/N performance against a Tomahawk-like cruise missile for four different months. For each month, curves are plotted for day (1 pm) and night (3 am), and for high (sunspot number (SSN) of 100) and low (SSN = 10) levels of solar activity. The dashed line at S/N = 4 (6 decibels) is an estimate of the minimum S/N required for detection assuming this is done by forming tracks. The poor daytime performance during the summer is due to high ionospheric absorption.


Target = Cruise Missile
Month = July
Signal/noise
decibels
70
60
50
40
30
20
10
0
−10
−20
−30
0
1,000
2,000
3,000
Ground range
kilometers
day, SSN = 100
night, SSN = 100
day, SSN = 10
night, SSN = 10


Target = Cruise Missile
Month = October
Signal/noise
decibels
70
60
50
40
30
20
10
0
−10
−20
−30
0
1,000
2,000
3,000
Ground range
kilometers
day, SSN = 10
day, SSN = 100
night, SSN = 100
night, SSN = 10

clearly within the realm of what is currently achievable. However, it is unclear (as data on the ultimate clutter rejection capabilities of OTH radars is not publicly available) if adequate clutter rejection is available for cruise missiles, particularly at night.[31]

OTH radars attempting to detect cruise missiles may also face a serious false-alarm problem. Such false alarms can arise from multipath propagation that causes a target to appear in more than one range cell, from scattering off meteor trails, and from scattering due to ionospheric disturbances. This can be a particularly serious problem for a long-range early-warning sensor, where confirmation of false alarms may be difficult.[32]

OTH-B Evaluation and Technical Prospects for Future OTH Systems

The OTH-B system, if completed, would, together with the North Warning System, provide complete coverage of the air approaches to North America for bomber-sized tar-

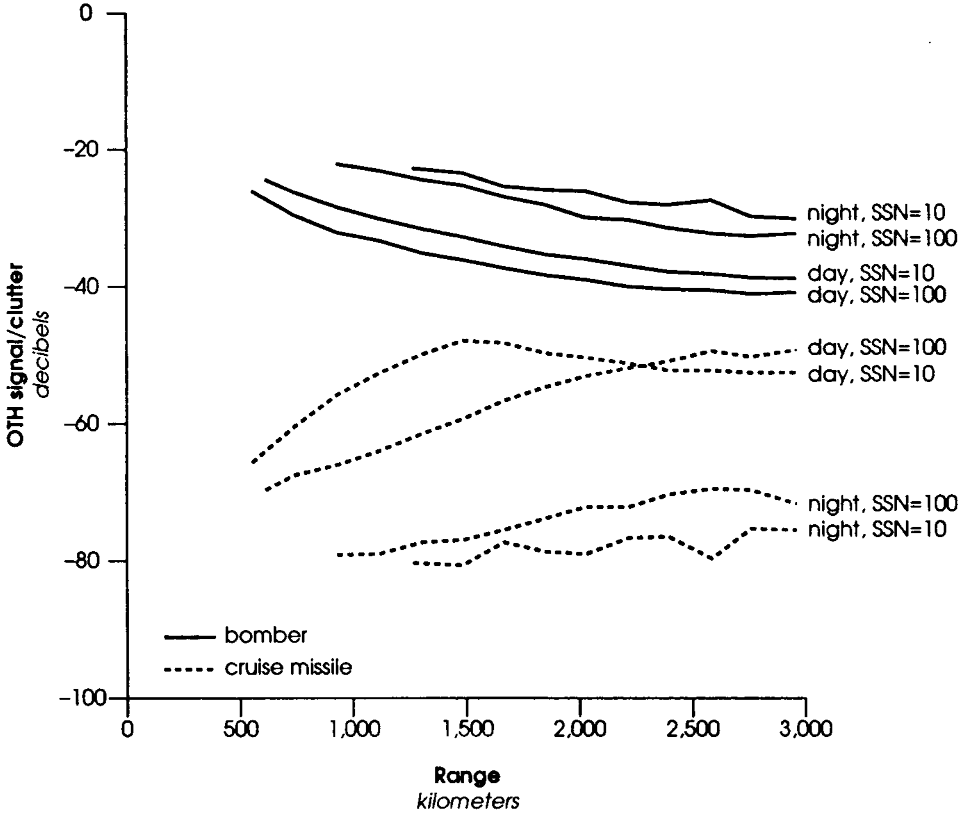


Figure B-2: OTH-B S/C for a Tomahawk-like cruise missile and for a bomber target for typical October conditions.

gets. It does not, however, appear to be capable of providing a reliable detection capability against a small-scale cruise missile attack. The estimates made here suggest that while the OTH-B system would be able to detect cruise missiles under favorable circumstances, it would not be able to do so during the significant fraction of the time when operating conditions are unfavorable, primarily at night, and especially at night during periods of low solar activity. A cruise missile surprise attack could be planned to exploit these times since they are predictable in advance.

Nevertheless, OTH radars provide a relatively inexpensive means of monitoring large areas, and the completion of the OTH-B system may be justifiable simply for the basic air surveillance capability it provides against airplanes. In addition, a complete OTH-B system could contribute to warning of cruise missile attacks during the daytime, could detect ALCM-carrying bombers even at night, and even at night might contribute enough uncertainty about the possibility of detection to contribute to deterring a small-scale cruise missile attack. Further, the system could also be upgraded to provide an improved capability against cruise missiles. However, it appears that it would be both very difficult and expensive to upgrade the OTH-B system enough to provide continuous, highly reliable warning of cruise missiles because the shortfall in detection performance is as large as two to three orders of magnitude in some situations.

The decision not to complete the OTH-B system and to partially or completely shut down the completed radars leaves much of the US perimeter with essentially no air surveillance coverage against low-flying cruise missiles. Although deactivated OTH-B radar sites could be reactivated in about six months if needed,[33] attempting to operate a recently reactivated system during a crisis might generate dangerous false alarms. The Navy's planned nine sector Relocatable-Over-the-Horizon Radar system could to some extent replace the OTH-B system, depending on how many sectors are built and where they are eventually located.[34] However, the ROTHR will be no more capable, and will probably be less capable, against cruise missiles than the OTH-B. Further, the ROTHR system is not designed to be integrated into the overall NORAD air surveillance system.[35]

A more advanced and powerful OTH radar is still a possible solution to the cruise missile warning problem. This approach might be particularly attractive because the long wavelengths used by OTH radars will make it difficult to reduce cruise missile RCS values via stealth techniques.[36] Thus an OTH system designer will probably face a constant, albeit small, cruise missile radar cross section rather than the continually shrinking RCS values confronting designers of systems that operate at higher frequencies. However, the analysis here suggests that an improvement in the S/N of at least two to three orders of magnitude will be needed, and improvements in S/C may be needed as well, if highly reliable cruise missile detection is to be possible.

Improvements in OTH performance could be achieved in a number of ways. The average transmit power could be increased, the length of the receive antenna could be increased, and the number of simultaneous receive beams significantly enlarged. A significant, although likely expensive, improvement would be the use of a two dimensional receive antenna array.[37] The improved understanding of the ionosphere and OTH operations that further research in this area would provide would also play an important role in improving OTH performance.

Taken together, it is not implausible that these improvements could produce an OTH system capable of reliably detecting small numbers of cruise missiles. However, continued research and development and, in particular, field testing will be required to establish whether this is feasible. Such a system is likely to be considerably more costly than the original $2.6 billion OTH-B system, and its ultimate technical feasibility is still unclear.

NOTES AND REFERENCES

1. Some useful general references on OTH radars include: J.M. Headrick, "HF Over-the-Horizon Radar," in Merrill I. Skolnik, ed., *Radar Handbook, 2nd edition* (New York: McGraw-Hill, 1990); Gary R. Nelson and George H. Millman, "HF Sky-Wave Backscatter Radar for Over-the-Horizon Detection," *IEE Radar Conference 1982* (London: Institution of Electrical Engineers, 1982), pp.97–100; W. Fenster, "The Application, Design, and Performance of Over-the-Horizon Radars," *IEE International Conference Radar-77* (London: Institution of Electrical Engineers, 1977) pp.36–40; James M. Headrick and Merrill I. Skolnik, "Over-the-Horizon Radar in the HF Band," *Proceedings of the IEEE* **62**, 6, June 1974, pp.664–673; E.D.R. Shearman, "Over-the-Horizon Radar," in M.J.B. Scanlon, ed., *Modern Radar Techniques* (New York: Macmillan, 1987). Discussions may also be found in some general radar references, such as chapter 14 of Merrill I. Skolnik, *Introduction to Radar Systems,* 2nd edition (New York: McGraw-Hill, 1980).

2. In regions of auroral activity, magnetic-field–aligned tubes of ionization are in rapid motion. Thus reflections off these ionization tubes have a large spectral width, so that Doppler techniques cannot be used to separate moving targets from this auroral clutter. See Shearman, "Over-the-Horizon Radar," pp.224–225.

3. The HF frequency band is crowded with a variety of civilian users. Not only could these noise sources degrade OTH effectiveness but OTH radars are often required to operate in such a way that they do not interfere with other users. Thus OTH radars must monitor the HF frequency band to locate clear regions of the spectrum for use. Narrow operating bandwidths help in this regard, but result in poor range resolution. Thus OTH radars have to make a trade-off between the lower noise level provided by a narrow bandwidth versus the poorer range resolution (and hence increased surface clutter) that it provides.

4. Fenster says detection performance is limited by propagation outages which occur approximately 5 percent of the time; see Fenster, "Application, Design, and Performance," p.38. On the other hand, Headrick says greatly inferior performance will occur only a few hours per year; see Headrick, "HF Over-the-Horizon Radar," p.24.27.

5. This minimum range results from practical radars having a minimum operating frequency and from the radars' antennas being designed to transmit or receive only at low elevation angles.

6. The complete 12 sector OTH-B program was to have cost $2.6 billion, or roughly $215 million per sector, including RDT&E costs.

7. For example, it has been estimated that OTH radars that are currently under construction or have been proposed for the United States (12 OTH-B sectors, 9 ROTHR sectors) would cover 20 percent of the earth's surface. David Hughes, "Navy Installs ROTHR System in Alaska to Protect Battle Groups in Pacific," *Aviation Week and Space Technology* **131**, 22, 27 November 1989, pp.69–80.

8. US General Accounting Office, *Over-the-Horizon Radar: Better Justification Needed for DoD Systems' Expansion*, GAO/NSIAD-91-61 (Washington DC: US General Accounting Office, 1991).

9. For a description of the Navy system, see Hughes, "Navy Installs ROTHR System." The Air Force's OTH-B system has roughly five times the transmit power of the Navy ROTHR, however, the ROTHR likely has superior clutter rejection capabilities because it forms narrower receive beams (sixteen 0.5° beams for ROTHR versus four

2.75° beams for OTH-B).

10. Three sectors on the east coast, three on the west coast, two in Alaska, and two to four for the central system.

11. At least one of the west coast sectors has been used to track targets in a demonstration mode. George Leopold, "Over-the-Horizon Radar Successfully Tracks Targets," *Defense News* **5**, 2, 8 January 1990, p.15.

12. The transmit gain is a measure of the ability of an antenna to focus emitted radiation in a given direction. It is given by the ratio of the maximum power per area produced by the antenna to that which would be produced if the antenna radiated isotropically.

13. Chris Bulloch, "Beyond the Far Horizon: USAF's Ionosphere-Bouncing Radar Finally Set to Go," *Interavia* **37**, 12, December 1982, pp.1302–1304. This figure applied to the experimental radar system (ERS), which had a shorter total antenna length (690 meters) than the operational OTH-B radar (1,110 meters). However, the increase in total length of the antenna is due to the addition of two segments to extend the range of operating frequencies from the 6.7–22.3 megahertz range used by the ERS to the 5–28 megahertz frequency range used by the operational system.

14. That is, 60°/7.5° = 8 azimuth steps in each of three 930 kilometer range sectors covering the total range of 930–3,330 kilometers.

15. For example, a cruise missile with a radial velocity of 900 km/hr (250 m/sec) would produce a Doppler shift of only 25 hertz at a frequency of 15 megahertz.

16. This is because the Doppler resolution is roughly equal to the inverse of the integration time.

17. The upper limit on integration time is imposed by the ionosphere and can vary from 25–50 seconds up to about 200 seconds depending on the ionospheric conditions and the ionospheric layer used. Joseph W. Maresca and James R. Barnum, "Theoretical Limitation of the Sea on the Detection of Low Doppler Targets by Over-the-Horizon Radar," *IEEE Transactions on Antennas and Propagation* **AP-30**, 5, September 1982, pp.837–845.

18. As the OTH-B has an average power of about 1 megawatt (12 transmitters, 90–100 kilowatts each), and an effective radiated power (the product of average power and transmit gain) of about 100 megawatts, its transmit gain must be about 20 decibels, a typical figure for a large OTH radar.

19. An OTH radar receive antenna generally has a greater gain than its transmit antenna. The OTH-B receive antenna length of 4,980 feet (1.52 kilometers) is significantly less than that of the WARF OTH radar in California, which is 2.55 kilometers long and has a gain of about 30 decibels. Taylor W. Washburn, Lawrence E. Sweeneny, Jr., James R. Barnum, and Walter B. Zavoli, "Development of HF Skywave Radar for Remote Sensing Applications," in *Special Topics in HF Propagation*, AGARD Conference Proceedings No. 263 (Neuilly-Sur-Seine, France: Advisory Group for Aerospace Research and Development, 1979). Thus the assumption of a receive gain of 30 decibels is likely to be optimistic for this radar.

20. Nelson and Millman, "HF Sky-Wave Backscatter Radar," p.98.

21. Both the SS-N-21 SLCM and the AS-15 ALCM appear to be somewhat longer than the Tomahawk. An upper limit on their length is probably about 7 meters. For the orientation considered here, this would give an RCS about 2.5 times (4 decibels) greater

than that of the Tomahawk, based on modeling the missile bodies as prolate spheroids.

22. Unlike many types of airplanes, where the wings and fuselage have comparable dimensions, current long-range cruise missiles have very small wings. The cruise missile RCS at OTH frequencies is therefore very highly polarization dependent, with the maximum RCS occurring when the electric field of the incoming radar wave is aligned with the cruise missile fuselage. In the case considered here, the cruise missile is assumed to be heading directly towards the radar, with the radar energy coming in from 30 degrees above the local horizontal. Thus a vertically polarized beam (at the transmitter) would give a greater RCS than a horizontally polarized one. However, as the polarization will undergo rotation as it passes through the ionosphere, the polarization at the target cannot be directly controlled by the radar. Thus the cruise missile RCS will fluctuate between an upper limit (vertical polarization) and a lower limit (horizontal polarization).

23. Headrick, "HF Over-the-Horizon Radar," p.24.26. This factor is not included in figure 3.

24. Propagation losses are generally of more importance to OTH radars than to line-of-sight radars (at least to ones operating below about 10 gigahertz). There are several sources of propagation losses, including ionospheric absorption, ionospheric attenuation, and ionospheric defocusing. In addition, as most OTH radar antennas are linearly polarized, and the ionosphere causes a polarization rotation, there can be a loss due to polarization mismatch at the receiver.

25. Headrick, "HF Over-the-Horizon Radar," pp.24.28–24.35. Headrick states that: "The analyses were made for a radar off the mid-Atlantic coast of the United States and should be a good approximation for any location where transmission paths are through the middle magnetic latitudes."

26. This is a rough estimate of this lower limit, based on Toomay's observation that "...a radar is essentially ineffective when $P_d < 0.5$ and $P_{fa} > 0.01$. This situation occurs at S/N = 6 decibels" (J.C. Toomay, *Radar Principles for the Non-Specialist,* 2nd edition [New York: Van Nostrand Reinhold, 1989] p.112). P_d is the probability of detection and P_{fa} is the probability of false alarm. This is probably an optimistic estimate for the radar.

27. However, it is important to bear in mind that the uncertainties involved in estimating the performance of an OTH radar can be very great. In particular, our estimates were based on a model which was for one particular location and orientation. Headrick's performance estimating curves are for a site in Maryland, near the Chesapeake bay, looking directly east. Headrick says that these curves should give a good approximation to the performance of a radar which transmits through the middle magnetic latitudes (Headrick, "HF Over-the-Horizon Radar, p.24.26) but it is possible that a careful choice of sites might produce a significant improvement in performance. The Air Force has stated that the location of the central US OTH-B site had been chosen to maximize the radar's ability to operate above 15 megahertz (US House of Representatives, Department of Defense Appropriations for 1989, part 6, p.562).

28. In Congressional testimony, the Air Force reported that the OTH-B system had good capability to detect cruise missiles when it could operate at frequencies above 15 megahertz (US House of Representatives, Department of Defense Appropriations for 1989, part 6, p.562). However, Headrick's charts show that the nighttime operating frequency will generally be well below 15 megahertz, although it may sometimes reach or exceed this value near the radar's maximum range (Headrick, "HF Over-the-Horizon

Radar," pp.24.28–24.35).

29. The range resolution must be multiplied by secθ, where θ is the grazing angle of the radar wave to the surface, in order to determine the range extent of the illuminated surface area. In this calculation, this term is neglected in computing the resolution cell size, as this effect is at most about 0.6 decibels. The radar wavelength and R^4 terms in this computation are from Headrick's charts (Headrick, "HF Over-the-Horizon Radar," pp.24.28–24.35).

30. The RCS of a clutter-producing surface can be described as a dimensionless clutter density. Thus a typical sea surface clutter density of –18 decibels means that, on average, each square meter of the ocean surface has an RCS of 0.016 m^2.

31. Headrick shows an example in which the clutter level at frequencies away from the clutter peak lies 80–90 decibels below the level of the clutter peak, which suggests that detection may be possible, at least under some circumstances (Headrick, "HF Over-the-Horizon Radar," pp.24.36–24.37).

32. In a 1978 experiment, the WARF OTH radar in California was used to monitor trans-Pacific airliner flights over a 24 hour period. A total of 50 out of 59 flights were detected, even though the average power of the WARF radar is only about one twentieth that of the OTH-B system. However, there were also four instances of detections being declared where no actual target existed. The reasons for these false alarms were listed as: 1. multipath plus operator overload; 2. radar hardware fault; 3. meteors plus spread-Doppler clutter; 4. cause unknown. W.B. Zavoli, T.W. Washburn, and D. Westover, *Twenty-Four Hour Continuous Aircraft Surveillance at WARF,* April 1978, SRI International, Technical Report 42, October 1972.

33. "USAF Weighs Plan for Limited OTH-B Operations in Maine," *Aviation Week and Space Technology* **134**, 17, 29 April 1991, p.69.

34. So far four ROTHR sites have been announced: Virginia (looking towards the Caribbean), Alaska, Guam, and Great Britain. US General Accounting Office, *Over-the-Horizon Radar,* p.2.

35. US General Accounting Office, *Over-the-Horizon Radar*, p.23.

36. The primary techniques for reducing the RCS of an aircraft are the use of radar absorbing materials and the shaping of the aircraft to direct the scattered radar energy away from the transmitting radar. Both techniques become ineffective at OTH wavelengths (10–60 meters), because the wavelength is much larger than the size of the shaped features or absorbing layers. However, active cancellation techniques might be a concern at these low frequencies.

37. Such a two-dimensional array would allow the use of multiple, narrow elevation receive beams. This would both improve S/N by increasing receiver gain and improve S/C by reducing the size of the earth's surface illuminated by the receive beam.