Technical information regarding the ICBM intercept calculations

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The purpose of this note is to provide readers of the 2024 POPA Strategic Ballistic Missile Defense Report [1] with technical information about the computations in the Report that are used to illustrate the potential capabilities of rocket interceptors to intercept two of North Korea's current ICBMs.

The kinematically allowed interceptor basing areas shown in the Report are based on the computations in [2]. These computations used models of North Korea's liquid-propellant Hwasong-15 and solid-propellant Hwasong-18 ICBMs launched toward possible targets in the continental United States, and interceptor models with burnout velocities of 4 km/s and 5 km/s when fired vertically from an altitude of 15 km—an appropriate altitude for firing them from a drone—–with the effects of atmospheric drag and gravity included, to illustrate the capability of such interceptors to intercept these ICBMs.

The burnout speeds of the particular interceptor models used in [2] would be significantly lower if they were fired from the ground or sea level instead of from an altitude of 15 km, due to the increased effects of atmospheric drag and gravity. However, their performance when fired from an altitude of 15 km can be used to assess approximately the intercept performance of interceptors that could achieve burnout speeds 4 km/s and 5 km/s when fired from the ground or sea level, because the most important performance parameter of an interceptor is its speed at burnout, regardless of the altitude from which it is fired.

ICBM Launch Site and Targets

For the sake of illustration, the authors of [2] chose a fictitious ICBM launch site in North Korea near Chunggang-up, in north-central North Korea, near its border with China. The precise latitude and longitude of their assumed launch site are 41.8° N and 126.93° E. This site is indicated by the red marker on the map shown in Figure 1.

ICBMs launched from this site toward the continental United States would be challenging for interceptors not based in China or Russia to intercept, because the resulting kinematically allowed interceptor basing areas have relatively little overlap with locations that would be far enough off the eastern coast of North Korea to be beyond the reach of North Korean sea and air defenses (for details, see [1]).

The two targets chosen to illustrate the reach-versus-time challenge for rocket interceptors attempting to intercept ICBMs in powered flight are Boston and Los Angeles, which represent, respectively, one of the most challenging targets to defend against attacks by North Korean ICBMs and a target that is easier to defend.

ICBM Models

The authors of [2] considered a liquid-propellant ICBM model intended to mimic the reported and inferred properties of North Korea's liquid-propellant Hwasong-15 ICBM, which was first tested in 2017. This ICBM is reported to have a first-stage burn time of about 128 seconds and a second-stage burn time of about 161 seconds, for a total burn time of

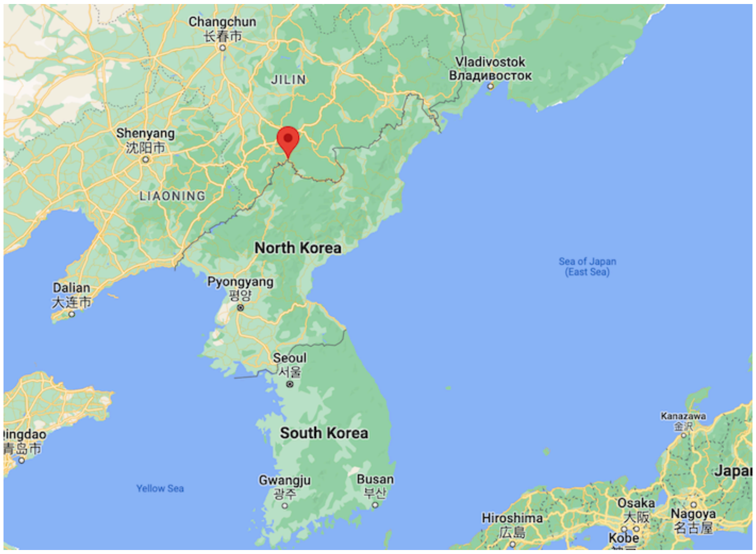

Figure 1: Map showing the location of the assumed North Korean ICBM launch site (latitude 41.8° N, longitude 126.93° E) used to compute the kinematically allowed basing areas for the drone-based interceptors considered in [1].

about 289 seconds [3]. Its trajectory during its 53-minute flight in 2017 was reported as having a maximum altitude of approximately 4,500 km and a range at impact of about 950 km. Following [2], the Study Group assumed that a plausible model of the Hwasong-15 could achieve this trajectory with a test payload of 400 kg.

The Study Group adopted the Hwasong-15 ICBM model used in [2]. The parameters of this model are listed in Table 1. They are similar to those assumed in [4], but were adjusted to give the Study Group's model approximately the same performance as that of the model used in [4], but for our assumed total burn time of 289 s rather than the total burn time of 299 s assumed in [4].

The Study Group also adopted the model of North Korea's solid-propellant Hwasong-18 ICBM used in [2], which was based on the S1 solid-propellant ICBM model used in the 2003 APS Boost-Phase Missile Defense Report [5]. The parameters of this model are listed in Table 2. It has a total burn time of 170 seconds. Because this burn time is so much shorter than the burn times of liquid-propellant ICBMs, the reach of a given interceptor during the Hwasong-18's powered flight is correspondingly much less.

ICBM Trajectories

When defending against the liquid- and solid-propellant ICBM models considered in this Report, the kinematically allowed basing areas for the two interceptor models considered in [2] were computed by assuming the model ICBMs are launched on a minimum-energy trajectory from the launch site to the target. This trajectory was computed in three di-

Table 1: The Study Group's model of the Hwasong-15 ICBM

Hwasong-15 model	**Parameter**	**Value**
Total mass	m_{tot}	51,650 kg
Total length	L	21.1 m
1st stage parameters		
1st stage total mass	$m_{\mathrm{tot},1}$	41,800 kg
1st stage usable fuel mass	$m_{\mathrm{fuel},1}$	36,784 kg
1st stage specific impulse (sea-level)	$I_{\mathrm{sp1,sea}}$	269 s
1st stage specific impulse (vacuum)	$I_{\mathrm{sp1,vac}}$	301 s
1st stage burn time	T_{b1}	128 s
1st stage diameter	d_1	2.0 m
2nd stage parameters		
2nd stage total mass	$m_{\mathrm{tot},2}$	9,100 kg
2nd stage usable fuel mass	$m_{\mathrm{fuel},2}$	7,826 kg
2nd stage specific impulse	I_{sp2}	325 s
2nd stage burn time	T_{b2}	161 s
2nd stage diameter	d_2	2.0 m
Other parameters		
Coefficient of drag	C_D	0.35
Payload mass	m_{payload}	675 kg

mensions, taking into account Earth's rotation during the ICBM's flight. Depending on the direction and range to the ICBM's target, placing it on a minimum-energy trajectory sometimes requires terminating the thrust of its final stage prior to the time when the final stage of a liquid-propellant ICBM would have exhausted its propellant or the final stage of a solid-propellant ICBM would have burned out. Air drag is included in the ICBM trajectory calculations reported in [2], with a drag coefficient of $C_D = 0.35$.

In computing the trajectories of the ICBM models in [2], the liquid-propellant Hwasong-15 model was programmed to perform a short pitchover maneuver before proceeding with its gravity turn. The pitchover was accomplished in under five seconds and without including lift forces, consistent with the nearly-instantaneous pitchover approximation that was used. The assumed start time and duration of the pitchover was found to make little difference to the sizes of the interceptor basing areas presented in [2] as long as the pitchover maneuver takes place less than a minute after the ICBM has been launched.

The analysis in [2] considered a boost-phase missile defense that would seek to intercept the assumed model of the Hwasong-15 260 seconds after it was launched from north-central North Korea (see Fig. 1), 30 seconds before its propellant would be exhausted. This analysis found that intercepts significantly later than 260 seconds after launch would benefit the defense little: after 260 s the interceptor is chasing the accelerating Hwasong-15 from behind (see [1] for further details).

The analysis in [2] also considered a boost-phase missile defense that would seek to inter-

Table 2: The Study Group's model of the Hwasong-18 ICBM*

Attribute	**Units**	**Stage 3**	**Stage 2**	**Stage 1**	**Total**
Diameter	meters	1.50	1.85	1.85	
Mass fraction		0.90	0.90	0.90	
m_{initial} [a]	tonne	1.93	8.81	41.1	41.1
m_{final}	tonne	1.02	2.61	12.0	
m_{inert}	tonne	0.10	0.68	3.2	
m_p [b]	tonne	0.91	6.12	29.0	
m_{shroud} [c]	kg				66.0
I_{sp}	seconds	277	275	265	
Thrust (average)	kN	62	254	1160	
Stage burn times	seconds	40	65	65	170
I_t	MN-s	2.4	16.5	75.4	
ΔV added (ideal) [a]	km/s	1.73	3.27	3.21	8.21

*See model S1, p.S262 of [5].
[a] Cumulative from left to right.
[b] Payload mass $m_p = 918\,\text{kg}$.
[c] Shroud eject occurs at 102 s, 28 s before second stage burnout.

cept a notional solid-propellant ICBM 145 seconds after it was launched from north-central North Korea (again see Fig. 1), 25 seconds before it burns out, to prevent its warhead from striking targets in the continental United States or in the territory of U.S. allies. As discussed in the Report [1], North Korea has successfully tested and is thought to have operationally deployed a solid-propellant ICBM, the Hwasong-18. This has profound implications for a boost-phase defense against North Korean ICBMs.

The performance parameters of the ICBM models used in [2] agree with the publicly available information about the performance of the Hwasong-15 and Hwasong-18, for plausible payload masses.

Interceptors

The performance parameters of the 4-km/s and 5-km/s interceptors used in [2] and adopted in the Report [1] are listed in Table 3. These interceptors are similar in scale to those proposed in [6]. The definition of the "burnout speed" used in [2] and in the Report [1] is the standard one (see [5], Table 4.1): the actual speed of the interceptor when it burns out on a vertical trajectory from its initial altitude, here assumed to be 15 km, with the effects of air drag and gravity taken into account. All else equal, the burnout speed of an interceptor is sensitive to the mass of its kill vehicle (KV): the lower the KV mass, the higher the burnout speed. The KV masses for the interceptors were chosen in [2] without considering whether a KV of this mass could achieve the required performance to achieve intercept. With the booster stacks assumed in [2], the interceptor burnout speeds are 4 km/s and 5 km/s for KV masses of 60 kg and 35 kg, respectively. The Report [1] shows the kinematically allowed basing areas for both burnout speeds. For the interceptors used in the Report [1], the corresponding ideal interceptor velocities (which ignore gravity and atmospheric drag) are 4.56 km/s and 5.56 km/s, respectively.

Table 3: The Study Group's drone-based interceptors

Interceptor models	**Parameter**	**4 km s^{-1} interceptor**	**5 km s^{-1} interceptor**
total mass	$m_{\mathrm{tot},1}$	532.3 kg	556.8 kg
total length	L	3.75 m	3.75 m
1st stage parameters			
1st stage propellant mass	m_{P1}	312.8 kg	345.6 kg
1st stage structural mass	m_{S1}	55.2 kg	61.0 kg
1st stage specific impulse	I_{sp1}	275 s	275 s
1st stage diameter	d_1	0.35 m	0.36 m
1st stage burn time	T_{b1}	25.0 s	25.0 s
2nd stage parameters			
2nd stage propellant mass	m_{P2}	88.7 kg	97.9 kg
2nd stage structural mass	m_{S2}	15.6 kg	17.3 kg
2nd stage specific impulse	I_{sp2}	285 s	285 s
2nd stage diameter	d_2	0.35 m	0.36 m
2nd stage burn time	T_{b2}	25.0 s	25.0 s
Other parameters			
Coefficient of drag	C_D	0.22	0.22
Kill vehicle mass	m_{KV}	60.0 kg	35.0 kg

Computation of Interceptor Basing Areas

The kinematically allowed basing areas computed in [2] assume the interceptors are fired from an altitude of 15 km. As discussed in [1], the kinematically allowed basing area for a given interceptor is the circular area on the Earth's surface inside or above which the interceptor could be positioned and be able to reach the target ICBM and terminate its thrust early enough to prevent its warhead from striking the defended area. The basing area computations in [2] and used in the Report [1] are focused on determining whether the interceptor can meet this "reach vs. time challenge". Being able to do this is a necessary but not sufficient condition for a boost-phase intercept attempt to be successful.

The kinematically allowed basing area concept assumes that the intercept point is known at the time the interceptor is fired, which generally is not the case. The radius of the kinematically allowed basing area depends on the time prescribed by the missile defense system's concept of operations to identify the type of missile and its direction of flight and construct an interceptor firing solution, and whether the concept of operations allows interceptors to be fired with no or minimal human input.

For an intercept attempt to be successful, the system's remote sensors and any sensors onboard the interceptor and its kill vehicle must be adequate to acquire and track the ICBM, and the interceptor and its kill vehicle must have enough thrust and be responsive enough to be able to adjust their trajectories to take into account deliberately evasive or unexpected incidental maneuvers by the ICBM during its powered flight. Other factors that will determine whether the intercept attempt is successful include whether sufficient time has been allowed to identify the type of missile and its direction of flight and construct an interceptor firing solution, and whether the performance of the system's communication, command, control, and battle management is adequate. These are just some of the myriad challenges that are not considered when constructing kinematically allowed basing areas but must be successfully overcome for an intercept attempt to be successful.

As in [2], the Report [1] assumes that interceptors are fired 65 s (45 s) after the liquid-propellant (solid-propellant) ICBM has been launched. According to the detailed simulations in [5], this is the earliest possible time an interceptor could be committed, based on the ability of a modern sensor system to determine the ICBM's direction of flight with enough precision to fire an interceptor. Hence the longest available interceptor flyout time to intercept a liquid-propellant ICBM like the Hwasong-15 ICBM 260 s after it has been launched is 195 s ($= 260\,\mathrm{s} - 65\,\mathrm{s}$), whereas the longest available interceptor flyout time to intercept a solid-propellant ICBM like the Hwasong-18 ICBM 145 s after it has been launched is 100 s ($= 145\,\mathrm{s} - 45\,\mathrm{s}$). These flyout times might be increased if distributed or improved sensors and machine learning allow as-yet-unquantified improvements in estimating the trajectory of the target ICBM quickly and deciding whether to fire interceptors. Typically the defense may wish to prescribe an additional "decision time" of 30 s or so, in order to gather additional information about the missile that has been launched and its direction flight to increase the probability of a successful intercept [5]. Prescribing additional time would reduce the radius of the kinematically allowed basing area correspondingly, as discussed in the Report [1].

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