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*High-Velocity Interceptors
for Boost-Phase Intercepts*

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by

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ABSTRACT

Brilliant kill packages with existing booster technology, warning, and command and control could produce interceptors that could reduce the effectiveness of theater attacks in the boost phase.

I. INTRODUCTION

Mature kinetic-energy interceptors have velocities in the range of 1-6 km/s, which are adequate for midcourse and terminal but not boost-phase intercepts.¹ Ground-based interceptors (GBIs), which are now the main thrust of the Strategic Defense Initiative (SDI), will handle² most of the threats³ prominent in the papers^{4,5} on which the current global protection against limited strikes (GPALS) is based.^{6,7} The Gulf War made the need for further development obvious. This paper explores higher velocity interceptors that could provide the needed capability.

II. RECENT LESSONS

The Gulf War showed that even SCUDs could fly trajectories and deploy enough extra objects to beat Patriots. These engagements suggested that SCUDs would do even better against the Patriot's hit-to-kill improvements for fundamental reasons.⁸

That pushes GPALS back up to higher altitudes on the missiles' trajectory, just as in SDI. But midcourse threats are ahead of the interceptors,⁹ and it appears that theater missiles can use existing dispensers to deploy multiple cluster munitions, gas, or biological agents as soon as they complete boost. If so, there is not much left for interceptors like THAAD to shoot at.

Thus, TMD now looks like SDI writ small--only it looks harder because TMD boost-phase timelines are so much shorter. Lasers and particle beams would be good, but they are immature.¹⁰ Brilliant pebbles (BPs) would be ideal, but there is concern that the deployments required would undercut arms control, as discussed in a recent debate with Garwin and Bethe.¹¹ That need not be the case,¹² but in arms control, perception is everything.^{13,14}

With a shot at the boost phase, the other phases might be able to pick up the rest. This report discusses the capabilities of ultravelocity slings for boost-phase intercept and their sensitivity to warning, acceleration, and velocity.

III. BACKGROUND ON SLINGS

The paper that introduced "brilliant pebbles" as boost-phase defenses also discussed their use as ultravelocity slings, which would use conventional boosters to accelerate small payloads to high enough velocities to reach intercontinental ballistic missiles (ICBMs) in boost from the US.¹⁵ For ICBMs such slings were inferior to space-based interceptors (SBIs) and were not developed. Slings' performance against ICBMs would degrade in time if ICBM boost and deployment times were reduced, because of the velocities required.

For theater missiles, slings could be effective--particularly if BPs are not permitted for arms control reasons. Deployed from the ground, ships, or air in the areas where the missiles were deployed, slings would have shorter ranges and could remain viable with attainable velocities. Forward basing eliminates Earth curvature and allows a single site to cover a

whole theater, overcoming the large inventories that penalize GBI theater missile defenses.¹⁶

IV. ANALYSIS

This section discusses the simplest model of sling capability and the main parameters in it. The analysis uses a geometric model of interceptor flyout and then comments on the magnitude of errors. Theater missiles on trajectories to range are taken to accelerate with constant velocity a_m to velocity $v_m = \sqrt{(gR)}$, where g is the value of gravity at the Earth's surface, which takes time $t_m = v_m/a_m$.

The interceptor must reach the missile by time t_m . It is taken to accelerate at a_i to velocity v_i , which takes time t_i . The time delay for detection and release is t_d . If $t_i < t_m - t_d$, the interceptor reaches full speed and its range is

$$r = v_i(t_m - t_d - t_i/2). \quad (1)$$

If $t_i > t_m - t_d$, the interceptor never reaches full speed and its range is

$$r = a_i(t_m - t_d)^2/2. \quad (2)$$

Theater missiles burn out at altitudes of 60-100 km. The vertical component of the trajectory is thus a 10% correction for ground ranges of 200 km and less for the longer ranges of interest here. Similarly, for interceptors with accelerations of >10 g's, the vertical component of thrust is a small correction.

The biggest theoretical error in Eqs. (1) and (2) is the neglect of atmospheric drag. However, that occurs in the first one or two scale heights of the atmosphere. It is calculable, and can be incorporated into the performance of the idealized interceptors discussed here.

The biggest practical problem is the neglect of kill package heating at high velocities, which could red out the sensor. For ground launches, that might necessitate a shroud over the sensor and command guiding the interceptor until the shroud could be dropped. That is a technical complication that is allowable in theater engagements.

It is argued that BPs can intercept at velocities of 10-14 km/s at altitudes down to 50-75 km. Ground-launched interceptors would be going no faster and would be looking up at a more benign background. Thus, they should be able to perform their function of commanding themselves to hit to kill.

The discussion above assumes that the missile trajectory is minimum energy. Depressed trajectories could complicate, but apparently could not negate, such intercepts.¹⁷

V. RESULTS

The predictions of the model of Section II are shown in the attached figures. This section discusses the performance of interceptors from the current 1 km/s to the 3-6 km/s of the first and second stages of BPs.

A. Ideal Interceptors

Figure 1 is for 1, 3, and 6 km/s interceptors with no delay ($t_d = 0$) and accelerations of 100 g's. The 1 km/s interceptor has an ideal range of only about 60 km, which is consistent with the inability of missiles with such velocities but much lower accelerations to achieve an engagement with missiles in boost in the Gulf War.

The 3 km/s interceptor gets out to about 200 km. That is a useful range, but less than the radius of most theaters. Thus, an interceptor with about the 3 km/s of the second stage of a BP could, if airborne over the theater, have useful engagement ranges and probabilities.

The 6 km/s interceptor gets out to 400-500 km. That would be enough to cover many theaters from safe airspace at their perimeter, but it is necessary to evaluate the degradations due to finite acceleration and delays.

B. Delay

Figure 2 shows the sensitivity of a 6 km/s interceptor with 100 g's to delays of 10, 20, and 40 s. The 40 s delay gives a significant penalty.

C. Interceptor Acceleration

Figure 3 shows the sensitivity of a 6 km/s interceptor with no delay to interceptor accelerations of 4, 16, and 64 g's. The penalty for 4 g's is significant. The curve for 16 g's is relatively close to that for 64 g's. That in turn is close to the curve for a 100 g accelerator on Fig. 1--especially for longer ranges.

D. "Real" Interceptors

Figure 4 shows the sensitivity of 3 and 6 km/s interceptor with a 10 s delay (about the minimum possible) to interceptor accelerations of 4, 16, and 64 g's. The penalties are worst for short ranges (short times). The penalty for 4 g's is significant--the curves are the same for 3 and 6 km/s because the interceptor never gets up to speed for ranges of interest.

With these "real-world" losses, the 3 km/s interceptors with 16-64 g's get out to 150-200 km; the 6 km/s interceptors out to 250-450 km. These ranges seem useful and achievable.

E. Corrected range

If the missile is launched toward the interceptor platform at a target behind it, a parabolic approximation to the missile's trajectory gives a shortening of the interceptor's flyout distance of $\delta r/R = g/\sqrt{2}a_m$, where a_m is the missile's acceleration. For a nominal $a_m \approx 4$ g's, $\delta r/R \approx 1/\sqrt{2} \cdot 4 \approx 1/5.7 \approx 0.18$. For a 600 km range the flyout would be reduced by $600 \text{ km} \cdot 0.18 \approx 106 \text{ km}$. For gravity turns, which are more nearly vertical, the range reduction could be less.

F. Launcher

Such interceptors could be based on the ground, in the air, or on ships. Each has advantages. Air has the possibility of moving forward or into the theater to minimize range to assure a boost-phase engagement opportunity. It also minimizes the drag

and heat loading on the interceptor and sensor. Ground and sea simplify basing at the cost of extra range.

G. Summary

These calculations for a constant acceleration missile are just applications of the Pythagorean theorem, but they at least give rough figures to refine the questions that should be put to more detailed treatments.

VI. ULTRA VELOCITY SLINGS

The calculations of Section III give useful values, but the 200-300 km ranges are too short for any margin against missiles launched from the interior of large countries or theaters. For that much higher velocities are needed. The technology for much higher accelerations developed in the defense programs of the 1960-70s and improved since. Ballistic Missile Defense¹⁸ uses 50-100 g's as typical of the interceptors for endoatmospheric engagements. The technology for producing such velocities, e.g., larger solid rockets and smaller grain sizes, is not reviewed here. The paragraphs below discuss the impact of their use in conjunction with small kill packages.

A. Background

A useful point of reference is the exoatmospheric intercept system (ERIS) interceptor, which uses a booster weighing $M_B \approx$ a few tons to accelerate a $M_E \approx 300$ kg kill package to $V_E \approx 5$ km/s.¹⁹ A booster of roughly that size should be able to accelerate a $M_{BP} \approx 30$ kg brilliant pebble to

$$V_E \approx V_E + c \cdot \ln(M_E/M_{BP}) \approx 5 \text{ km/s} + 2.5 \cdot 2.3 \approx 16.7 \text{ km/s. (3)}$$

The BP kill package's final velocity is the 5 km/s of the booster, plus the ≈ 5.8 km/s of the extra stage, plus the ≈ 6 km/s of the pebble, for a total of about 16.7 km/s, less some for course correction. Still higher velocities could be achieved with bigger, but manageable, rockets.

Theater engagements are not at the margin. Hence they don't have to be cost effective at the margin. But they shouldn't be outrageous. A rough guide to their cost exchange is the ratio of the missile and interceptor masses, which is roughly

$$\text{Mass Ratio} = M_W e^{v_m/c} / M_{BP} e^{v_i/c}, \quad (4)$$

where M_W is the mass of the missile's warhead and c the specific exhaust ($I_{sp} g$), which is taken to be about the same for both. Thus, $e^{v_m/c} / e^{v_i/c} = e^{-(v_i - v_m)/c} \approx e^{-(15-5)/2.5} \approx 2 \cdot 10^{-2}$ is small for large sling v_i , but $M_W / M_{BP} \approx 100 \text{ kg} / 3 \text{ kg} \approx 30$, so the product could remain near unity. Slings are not necessarily at a disadvantage in theater engagements.

B. Results

Figure 5 shows the predictions for 16 g interceptors with velocities for $v_i = 6, 12$, and 18 km/s ; Fig. 6 shows the 32 g interceptors. In the former, the ranges for 12 and 18 km/s are about the same, indicating that they are accelerating throughout. The curve for 6 km/s again shows saturation. For $600\text{--}800 \text{ km}$ missile ranges the interceptors ranges are $200\text{--}300 \text{ km/s}$, about as above.

Figure 6 shows the predictions for 32 g interceptors. The 6 km/s interceptor saturates beyond about 250 km , but the 12 and 18 km/s go up to $400\text{--}600 \text{ km}$ ranges for missiles with ranges of $600\text{--}800 \text{ km}$. Thus, even with finite delays and accelerations it is still possible for such slings to cover full theaters from their perimeters.

C. Basing

For very high velocities the basing consideration are more restrictive. Ground or ship basing is attractive, given the size of the rockets, but maximizes the drag on the interceptor and heat load on its sensor. The loads could be greater than those on re-entering BPs. An intermediate basing is at $20\text{--}30 \text{ km}$ altitude on remotely piloted vehicles (RPVs, a.k.a. "brilliant buzzards") for which the interceptor's rocket forms the RPV's body.²⁰ If their sensors don't red out, they could give the

defense a shot at the boost phase with largely existing technology. The RPVs would be demanding. Ideally, they would remain aloft for hours or days at high altitudes with significant payloads and still be ready to fly out on a few second's notice.

VII. SUMMARY AND CONCLUSIONS

Mature kinetic-energy interceptors have velocities in the range of 1-6 km/s, which are adequate for midcourse and terminal but not boost-phase intercepts. Boost-phase intercepts, which are of increasing importance, require more velocity and acceleration. They are available through ultravelocity slings, which were introduced in the same paper with brilliant pebbles. They use conventional boosters to accelerate small payloads to high enough velocities to reach missiles in boost.

The analysis uses the simplest geometric model of sling capability and parameters. The main theoretical error is the neglect of atmospheric drag; the main practical error is the neglect of sensor heating. Even with real-world delays and finite accelerations, slings can achieve ranges of 300-400 km.

The slings could be based on the ground, in the air, or on ships. Air platforms can move forward or into the theater to minimize range. They also minimize the drag and heat loading on the interceptor and sensor. Ground and sea simplify basing at the cost of extra range.

The longer ranges needed for margin can be achieved with larger, existing rockets with higher accelerations. Existing components could reach ≈ 20 km/s. Their mass exchanges would still be favorable. High acceleration and velocity interceptors produce ranges up to 400-600 km ranges for missiles with ranges of 600-800 km.

Thus, even with finite delays and accelerations it is still possible for such slings to cover full theaters from their perimeters. For very high velocities the basing consideration is more restrictive. "Brilliant buzzards" could give the defense a shot at the boost phase with largely existing technology. Thus, brilliant sensors with existing booster technology, warning, and

command and control could produce interceptors that could reduce the effectiveness of theater attacks in the boost phase. This capability could be needed in the long term, which apparently starts in about a decade.

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Fig. 1. Int. range vs missile range

$a = 100g, t_d = 0$

Fig. 2. Range vs delay time

$a = 100g, v_i = 6$ km/s

Fig. 3. Range vs intercept acccel

Fig. 4. Range vs intercept acccel

Fig. 5. Range vs intercept velocity

Fig. 6. Range vs intercept velocity

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