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Modeling the Performance of Hypersonic Boost-Glide Missiles

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ABSTRACT
The United States, Russia, and China are developing an array of hypersonic weapons—maneuverable vehicles that carry warheads through the atmosphere at more than five times the speed of sound. Proponents claim that these weapons outperform existing missiles in terms of delivery time and evasion of early warning systems. Here, we report computational modeling of hypersonic boost-glide missile flight which shows that these weapons travel intercontinental distances more slowly than comparable ballistic missiles flying depressed trajectories, and that they remain visible to existing space-based sensors for the majority of flight. Fundamental physical limitations imposed by low-altitude atmospheric flight render hypersonic missiles an evolutionary—not revolutionary—development relative to established ballistic missile technologies. Misperceptions of hypersonic weapon performance have arisen from social processes by which the organizations developing these weapons construct erroneous technical facts favoring continued investment. The modeling reported here provides a basis for rigorous, quantitative analysis of hypersonic weapon performance.

Introduction

Hypersonic weapons comprise an emerging class of missile technologies—maneuverable vehicles that carry warheads through the atmosphere at more than five times the speed of sound.[1] Their flight characteristics are distinct from those of typical ballistic missiles, which spend most of flight above the atmosphere and are capable of only limited maneuverability, and from those of subsonic or supersonic cruise missiles, which travel through the atmosphere but fly more slowly.

The United States, China, and Russia are currently racing to develop these weapons, and each plans to field a wide array of hypersonic systems in the coming decades.[2] The most recent U.S. defense budget, for example,

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dedicates $3.2 billion to hypersonic weapon programs, representing about 3% of the total defense research and development budget.[3] China is also investing heavily in both hypersonic development infrastructure and weapon systems, reportedly outpacing the United States in testing of these technologies.[4] Russia, reportedly the first nation to deploy a hypersonic missile, characterizes these weapons as a centerpiece of its security strategy and has extensively tested at least three distinct hypersonic systems.[5]

This nascent hypersonic arms race is premised on claims that the supposedly unprecedented capabilities of these weapons portend a revolution in missile warfare—claims that pervade the news media, governmental statements, and the scholarly literature. Hypersonic missiles are commonly depicted as a "game changer."[6] With allegedly "unmatched speed," these weapons are said to "hit over-the-horizon targets in a fraction of the time it would take existing ballistic or cruise missiles."[7] In short, proponents assert that "developments in hypersonic propulsion will revolutionize warfare by providing the ability to strike targets more quickly."[8] This claimed speed advantage is ostensibly accompanied by near-immunity to detection, rendering hypersonic weapons "nearly invisible" to existing early warning systems.[9] Together, these capabilities will purportedly "greatly compress decision and response times" in a hypersonic strike, leaving those targeted with "insufficient time … to confidently identify and confirm the nature of an incoming attack, let alone to decide how to respond."[10]

Despite these claims, the precise capabilities of hypersonic missiles remain uncertain and controversial. In contrast to the common depiction of these weapons as a revolution in missile warfare, several recent analyses suggest they may offer minimal advantage over existing missile technologies.[11] Detailed, quantitative, open-source technical assessment is necessary to clarify the capabilities of this emerging technology and its probable effects on international security.

This article reports the results of computational modeling of hypersonic boost-glide vehicle flight. Our analysis indicates that a hypersonic missile will travel intercontinental distances more slowly than a comparable ballistic missile flying a depressed trajectory. Furthermore, hypersonic missiles will remain visible to existing space-based early warning systems for the majority of flight. Ultimately, these results show the performance and strategic implications of hypersonic weapons to be broadly comparable to those of established ballistic missile technologies. While hypersonic weapons exhibit some modest advantages in terms of, for example, maneuverability, fundamental physical limitations imposed by low-altitude atmospheric flight render these weapons at best an evolutionary—not revolutionary—advancement. The persistence of misperceptions regarding hypersonic weapon performance has resulted from social processes by which erroneous technical facts have been socially constructed and promulgated by organizations developing these weapons.

The first section of this article presents a mathematical model of the flight of a notional hypersonic vehicle. Computational results, and their implications for hypersonic weapon performance, are presented next. The last section examines the social origins of misperceptions regarding hypersonic weapon capabilities. The article concludes with discussion of further questions regarding hypersonic weapon capabilities which the modeling approach reported here might address.

Computational modeling of hypersonic flight

Hypersonic weapons can be sorted into two distinct categories: cruise missiles and boost-glide vehicles.[12] The former operate much like typical subsonic and supersonic cruise missiles—using air-breathing engines to power themselves through the atmosphere—but fly at higher speeds. Yet hypersonic cruise missiles are unlikely to match the speeds or ranges achievable by boost-glide vehicles, which are accelerated to extremely high velocities on rocket boosters similar to those used to launch ballistic missiles. They then proceed to glide, unpowered, through the upper atmosphere until reaching their target. Because boost-glide systems represent the forefront of hypersonic missile performance in terms of speed and range, and because they are the focus of most current development activity, our analysis focuses on this class of missile.

Typical flight of a hypersonic boost-glide weapon can be divided into six stages: boost, ballistic, reentry, pull-up, glide, and terminal phases.[13] In the boost phase, a rocket booster accelerates the missile carrying the hypersonic vehicle until the booster exhausts its fuel, at which point it detaches from the glide vehicle and falls back to Earth. In the ballistic phase, the vehicle travels above the atmosphere on a ballistic trajectory under only the influence of gravity. Both of these phases are comparable to a ballistic missile launch. Hypersonic trajectories diverge from those of ballistic missiles in the reentry and pull-up phases. Here, the vehicle pierces the upper atmosphere, then slows its descent to enter a stable glide trajectory. In the glide phase, the vehicle generates aerodynamic lift to sustain near-level flight. Finally, in the terminal phase, the glider dives toward its target.

We model the boost and ballistic phases using standard equations of motion for ballistic missile flight (Appendix).[14] The complex dynamics of the pull-up phase, which are difficult to accurately simulate with the available data on glide vehicle parameters, are treated analytically using a simple mathematical approach reported by Acton.[15] We have developed a new computational model to simulate in detail the glide and terminal phases,

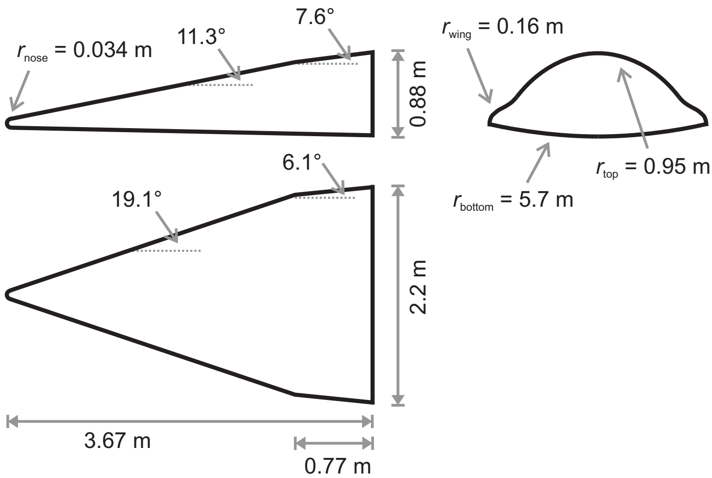

Figure 1. The HTV-2 glider geometry used in this analysis. Because we obtain aerodynamic parameters (ballistic coefficient and lift-to-drag ratio) from analysis of flight test data, our trajectory results are insensitive to the assumed vehicle geometry. Calculated surface heating and infrared light emission, however, do depend on this geometry.

which constitute the majority of a typical long-range hypersonic flight trajectory.

The notional glide vehicle modeled here is based on the Hypersonic Technology Vehicle 2 (HTV-2), an experimental glider jointly developed and tested by the U.S. Air Force and the Defense Advanced Research Projects Agency (DARPA).[16] This system is commonly considered a prototypical intercontinental-range hypersonic glide vehicle. Several recent analyses of its flight characteristics have been published in the open literature, providing useful data for modeling.[17] We assume a roughly triangular pyramidal geometry based on that reported by Niu et al., as shown in Figure 1.[18] Based on prior analysis of HTV-2 test flights, we assume a glider mass of $m = 1{,}000\,\mathrm{kg}$, a constant lift-to-drag ratio of $L/D = 2.6$, and a ballistic coefficient of $\beta = m/(C_d A) = 13{,}000\,\mathrm{kg/m^2}$, where C_d is the drag coefficient and A is the effective glider cross-sectional area.[19] These aerodynamic parameters are in good agreement with those reported elsewhere for wedge-shaped hypersonic gliders.[20]

Flight trajectory

We model atmospheric flight in the glide and terminal phases over a spherical, non-rotating Earth using the three-dimensional coordinate system illustrated in Figure 2. Four forces govern flight trajectories in this model: gravity, lift, drag, and an apparent centrifugal force. The influence of these forces is expressed in six equations of motion describing velocity (v), flight angles measured relative to the local horizontal (γ) and azimuthally from

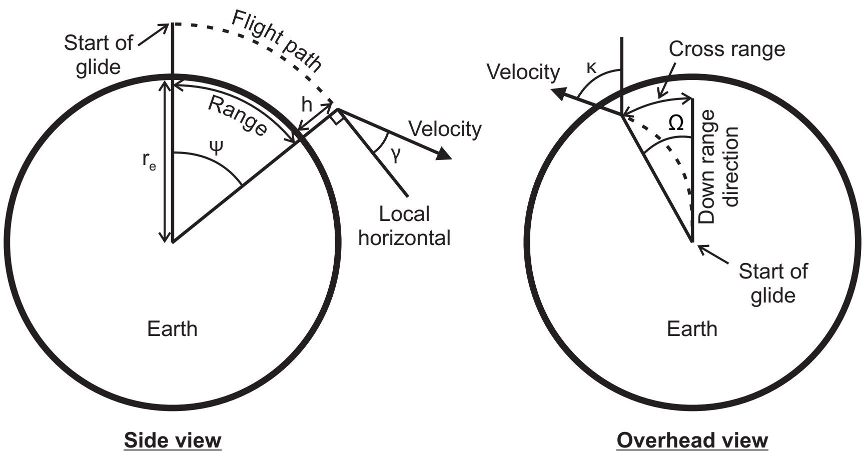

Figure 2. The coordinate system used in the hypersonic flight model, shown from both side (left) and overhead (right) perspectives. Six trajectory variables are modeled: velocity (v), flight angles relative to the local horizontal (γ) and measured azimuthally from the down-range direction (κ), down-range angle over Earth (Ψ), cross-range angle over Earth (Ω), and altitude (h). Down-range and cross-range distances, measured over Earth's surface, are given by Ψr_e and Ωr_e, respectively.

the down-range direction (κ), down-range angle over Earth (Ψ), cross-range angle over Earth (Ω), and altitude (h), all as a function of time:

$$\frac{dv}{dt} = -\frac{C_d A}{2m}\rho v^2 - g\sin\gamma \tag{1}$$

$$\frac{d\gamma}{dt} = \frac{v\cos\gamma}{r_e + h} + \left({}^{L}/_{D}\right)\left(\frac{C_d A}{2m}\right)\rho v\cos\sigma - \frac{g}{v}\cos\gamma \tag{2}$$

$$\frac{d\kappa}{dt} = \left({}^{L}/_{D}\right)\left(\frac{C_d A}{2m}\right)\frac{\rho v\sin\sigma}{\cos\gamma} \tag{3}$$

$$\frac{d\Psi}{dt} = \frac{v\cos\gamma\cos\kappa}{r_e} \tag{4}$$

$$\frac{d\Omega}{dt} = \frac{v\cos\gamma\sin\kappa}{r_e} \tag{5}$$

$$\frac{dh}{dt} = v\sin\gamma \tag{6}$$

where C_d is the vehicle's drag coefficient, A is its effective cross-sectional area, m is its mass, ρ is the atmospheric density, g is the acceleration due to gravity, r_e is Earth's radius, L/D is the vehicle's lift-to-drag ratio, and σ is the vehicle's roll angle.[21] We calculate atmospheric density using the 1976 U.S. Standard Atmosphere. Down-range and cross-range distances, measured over Earth's surface, are given by Ψr_e and Ωr_e, respectively.

We simulate flight beginning with a velocity vector oriented horizontal to Earth's surface. We assume an initial equilibrium altitude at which vehicle weight is equal to the sum of the lift generated by the vehicle and the apparent centrifugal force arising from its flight over a spherical Earth, as given by:

$$\frac{\left(L/_{D}\right)\rho v^2 g}{2\beta} + \frac{v^2}{r_e} - g = 0 \quad (7)$$

We calculate the glide trajectory by integrating the equations of motion (Equations (1)–(6)) over time using a second-order Runge-Kutta (mid-point) method. Maneuvering is simulated via variation of the glide vehicle roll angle; for nonzero angles a portion of the lift force acts in the horizontal direction, perpendicular to the vehicle's velocity direction.

In the terminal phase we model an inverted dive maneuver in which the glider turns upside down (corresponding to a roll angle of $\sigma = 180°$), such that the lift force is oriented toward the ground. This yields a faster, more efficient traversal of the dense lower atmosphere.[22] An inverted dive was reportedly used in flight tests of the HTV-2.[23]

Aerothermal heating

As a glider traverses dense atmosphere at hypersonic speeds, shock waves form in the nearby air. Much of the kinetic energy the glider loses as it is slowed by atmospheric drag is transferred to this surrounding air, yielding intense aerothermal heating. A portion of this heat is deposited to the vehicle, producing extreme temperatures on its outer surfaces.

To model this heating, we consider the case of turbulent gas flow over a non-ablative, catalytic glider surface. We calculate heat transfer to this surface using phenomenological equations reported by Tauber et al. for heat transfer in hypersonic flows.[24] At the stagnation point (the tip of the glider leading edge), the heat flux to the vehicle surface is approximated as:

$$\left(\frac{dq}{dt}\right)_{SP} = \frac{1.83 \times 10^{-4}}{\sqrt{r_n}}\left(1 - \frac{h_w}{h_0}\right)\rho^{0.5} v^3 \quad (8)$$

where dq/dt is the heat flux in J/m^2s, r_n is the radius of the glider's leading edge in m (0.034 m for the glider geometry shown in Figure 1), h_w is the vehicle wall enthalpy per unit mass, h_0 is the stagnation enthalpy per unit mass, ρ is the atmospheric density in kg/m^3, and v is the vehicle velocity relative to air in m/s. The stagnation enthalpy is approximated as $h_0 = v^2/2 + (2.3 \times 10^5$ J/kg), and the wall enthalpy as $h_w = 1{,}000\,T_w$ J/kg, where T_w is the wall temperature in K.[25]

We calculate heating of the remainder of the vehicle surface by approximating it as a triangular pyramid with four sides (two on the upper surface, one on the lower, and the base of the pyramid at the rear of the glider) oriented at different angles relative to the air flow direction. This allows for the use of phenomenological equations, again obtained from Tauber et al., for heat transfer to flat plates in turbulent hypersonic flow. When $v > 4\,\mathrm{km/s}$:

$$\left(\frac{dq}{dt}\right)_{FP} = 2.2 \times 10^{-5}\left(\frac{(\cos\theta)^{2.08}(\sin\theta)^{1.6}}{x^{0.2}}\right)\left(1 - \frac{1.11h_w}{h_0}\right)\rho^{0.8}v^{3.7} \tag{9}$$

and when $v \leq 4\,\mathrm{km/s}$:

$$\left(\frac{dq}{dt}\right)_{FP} = 3.89 \times 10^{-4}\left(\frac{(\cos\theta)^{1.78}(\sin\theta)^{1.6}}{x^{0.2}}\right)\left(1 - \frac{1.11h_w}{h_0}\right)\left(\frac{556}{T_w}\right)^{0.25}\rho^{0.8}v^{3.37} \tag{10}$$

where θ is the angle between the vehicle surface and the freestream flow, x is the distance along the vehicle surface in meters, and T_w is the temperature of the vehicle wall in K. This approach shows good agreement with the results of computational fluid dynamics calculations.[26]

As heat flows from the surrounding gas to the surface of a hypersonic vehicle, that surface simultaneously sheds heat through thermal radiation. Assuming a non-ablative aeroshell with a perfectly insulated interior and neglecting thermal conduction along the shell, a glider in steady-state flight will achieve thermal equilibrium at the radiative-adiabatic limit.[27] At this limit, the heat flux from the gas to the vehicle is equal to the heat flux radiated by its surface, as given by the Stefan-Boltzmann law:

$$\left(\frac{dq}{dt}\right)_{rad} = \varepsilon\sigma {T_w}^4 \tag{11}$$

where ε is the surface emissivity and σ is the Stefan–Boltzmann constant.[28] We take the emissivity of the HTV-2's carbon aeroshell to be $\varepsilon = 0.85$.[29] Setting Equations (8), (9), or (10) equal to Equation (11) yields T_w as a function of position on the surface of the vehicle.

Thermal radiation in the infrared spectrum

The surface of a hypersonic glide vehicle typically reaches temperatures of thousands of Kelvin during glide, producing substantial thermal radiation across the infrared (IR) spectrum.[30] When sufficiently intense, this IR signature can be detected by space-based IR sensors of the sort that the United States and Russia use in their missile early warning systems.[31]

To quantify this IR emission, we calculate the spectral radiance L (radiant flux per unit solid angle per unit projected area per unit frequency) of a glider using Planck's law:

$$L(\lambda, T_w) = \left(\frac{2\varepsilon hc^2}{\lambda^5}\right)\left(\frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}\right) \tag{12}$$

where λ is the wavelength of light, h is the Planck constant, c is the speed of light, and k_B is the Boltzmann constant.[32] We then double integrate Equation (12) over the wavelength band of interest and the observed area of the glider surface, yielding the total observed radiant intensity (radiant flux per unit solid angle) of the vehicle. The results reported here assume an observer situated directly overhead; alternate viewing angles would increase or decrease the observed intensity in proportion to the corresponding change in observed area. Atmospheric attenuation has a minor effect on IR transmission to satellites from typical hypersonic flight altitudes (tens of kilometers), and is therefore neglected.[33]

Computational results

Flight trajectory

The flight of a hypersonic vehicle in the glide and terminal phases is governed, in large part, by atmospheric drag. While ballistic missiles spend the majority of their flight in outer space where air density is negligible, hypersonic glide takes place within the atmosphere where air density is sufficiently high to generate the lift necessary for sustained flight. As expressed in a glider's *L/D* parameter, the generation of lift is unavoidably accompanied by the proportional generation of drag. This drag reduces a glider's velocity, which in turn limits its achievable range and maneuvering capability.

Figure 3 shows the calculated glide phase velocity of the modeled hypersonic vehicle as a function of glide range for flight straight down-range with no cross-range maneuvering. Data are presented for a range of initial glide velocities, which will vary with the booster rocket and the boost, reentry, and pull-up trajectories chosen for a particular hypersonic missile launch. Based on Acton's analysis of HTV-2 flight tests, initial glide velocities of roughly 6 km/s can be considered typical for intercontinental-range systems.[34] In all cases, drag rapidly slows the glider. For example, the velocity of a missile beginning glide at $v = 6$ km/s is halved after 6,000 km of glide.

As a glider's velocity decreases due to drag, its equilibrium flight altitude also decreases, assuming a constant value of L/D and a constant relationship between v and the generated lift (Equation (7)).[35] Thus, as it slows, a

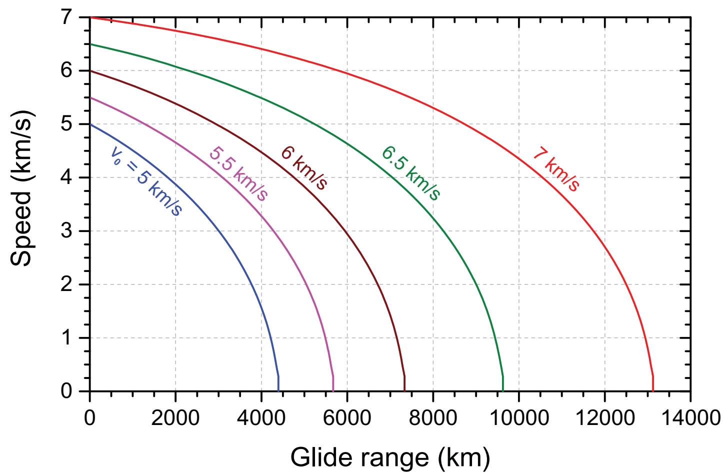

Figure 3. Hypersonic vehicle speed as a function of glide range for various initial glide speeds, illustrating how atmospheric drag slows the vehicle throughout the glide phase.

glider must drop to lower altitudes where denser air can provide sufficient lift to keep it aloft. Continuous hypersonic flight is therefore constrained to a relatively narrow altitude-velocity corridor.[36] Figure 4 shows calculated glide altitudes as a function of glide range under the same flight conditions considered in Figure 3.

These results show good agreement with the prior literature. For example, Acton estimated an achievable range of ~7,500 km for an HTV-2 with an initial glide speed of 6.1 km/s and initial glide altitude of ~50 km.[37] For these conditions, our model predicts a similar maximum range of 7,630 km.

Drag effects on glide speed and altitude limit the achievable hypersonic missile delivery times. Figure 5 displays the calculated glide time necessary for the modeled vehicle to reach a certain glide range. At long ranges, such as those associated with intercontinental strikes, the drag penalty on delivery time can be substantial.

While the above analysis concerns straight flight in the down-range direction, drag also limits cross-range maneuverability. Figure 6 shows the calculated flight paths of a glider maneuvering in the cross-range direction using a variety of vehicle roll angles. The ends of these flight paths approximately trace one-half of the area threatened by a missile initially gliding in the down-range direction. While substantial cross-range maneuvering is possible, it entails a reduction in the total flight path length. This is because a glider must roll in order to turn, redirecting a portion of the lift force toward the cross-range direction. The corresponding reduction in the lift force acting counter to gravity results in a faster loss of altitude and, therefore, velocity.[38]

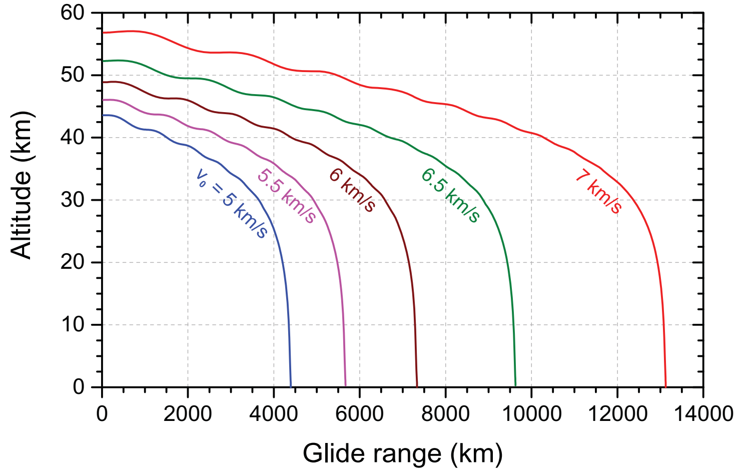

Figure 4. Hypersonic vehicle altitude as a function of glide range for various initial speeds. As drag slows the vehicle, the lift it generates (at a constant angle of attack) decreases. The glider therefore drops to lower altitude, at which increased atmospheric density yields a greater lift force for the same velocity. Minor oscillations about the equilibrium flight altitude, called phugoid motion, result from the dynamics of this process. These could be damped by active control of the vehicle.

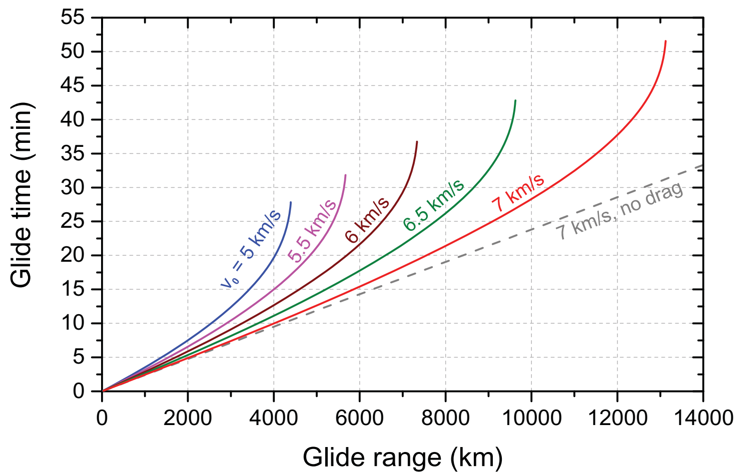

Figure 5. Glide time as a function of glide range for various initial speeds. The gray dashed line corresponds to an initial speed of 7 km/s in the absence of atmospheric drag. Curvature of the solid lines results from the effects of atmospheric drag.

Comparison with ballistic missiles

The strategic implications of hypersonic weaponry depend on its performance relative to that of ballistic missiles, which currently represent the state-of-the-art in fast, long-range warhead delivery.[39] Long-range ballistic missiles reach velocities comparable to those of hypersonic boost-glide systems, since they are launched on similar or identical rocket boosters.

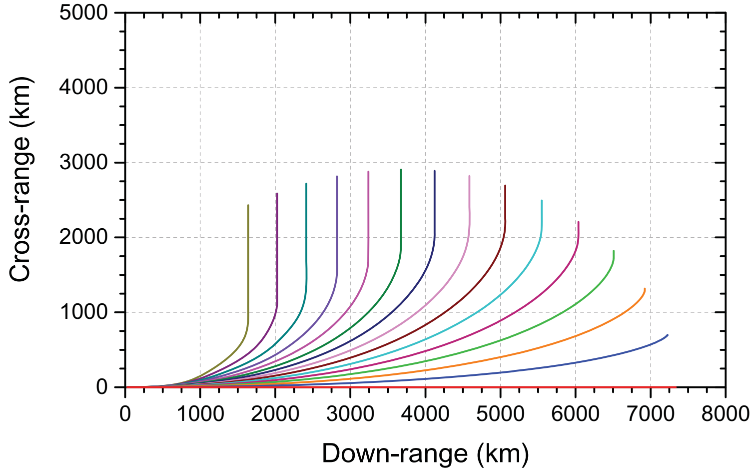

Figure 6. Flight trajectories of vehicles beginning glide with v = 6 km/s and roll angles varying in 5° increments from 0 to 70°. To maximize cross-range travel, the roll angle is reset to 0° once the glider is traveling directly cross-range. The ends of these flight paths trace one half of the approximate area threatened by a missile at the start of glide.

Unlike gliders, they then spend most of their flight high above the atmosphere where they are not subjected to drag forces. However, this high, arcing flight increases the flight path length necessary to reach a given range, relative to the low-altitude flight paths of hypersonic gliders.

To determine the relative capabilities of hypersonic and ballistic missiles we modeled intercontinental-range flight of both missile types, comparing their flight times and reentry speeds.[40] To facilitate comparison, identical Minotaur IV booster rockets were modeled in both cases. This three-stage, solid-fueled modification of the Peacekeeper intercontinental ballistic missile (ICBM) was used in flight testing of the HTV-2 and has been considered for future use in deployed U.S. hypersonic weapons.[41] Booster parameters were obtained from prior analysis by Wright.[42]

For the hypersonic case, we modeled a boost phase trajectory based on that used in HTV-2 flight testing.[43] For the reentry and pull-up phases, we used Acton's results from analysis of HTV-2 flight tests.[44] Under these assumptions, the hypersonic vehicle begins its pull-up phase, after reentering the atmosphere, at a speed of 7.1 km/s. It subsequently begins glide 3,100 km down-range from its launch point, 10.1 minutes after launch, at an altitude of 49 km and a speed of 6.1 km/s.

For the ballistic case, we modeled two distinct trajectories.[45] The first is a typical minimum energy trajectory (MET), which is the most energy-efficient trajectory for a given range. It sends the warhead arcing over 1,000 km above Earth before it falls to its target. For this trajectory, the rocket booster burn time was varied to achieve the desired missile range.

The second is a depressed trajectory (DT), so named because the missile turns sharply toward the down-range direction during the boost phase, yielding a small angle with respect to the local horizontal at the end of boost and, consequently, a much lower apogee. This trajectory reduces the missile's total flight path length necessary to reach a given range, compared with a minimum energy trajectory, resulting in shorter delivery times. The depressed trajectory calculation assumes a boost phase turn similar to, but less severe than, that used in HTV-2 flight testing.[46] The flight angle at booster burn-out was varied to achieve the desired missile range. To facilitate direct comparison with the hypersonic case, we assume a ballistic missile reentry vehicle mass of 1,000 kg (equal to the HTV-2 mass used in this modeling) so that the two systems exhibit essentially the same speed at booster burn-out.[47]

Figure 7 shows the resulting trajectories for hypersonic and ballistic missiles delivered to targets 8,100 km away from the launch point (corresponding to 5,000 km glide, in the hypersonic case). Figure 8 shows the total warhead delivery time, from launch to impact, for each missile as a function of range.

These results show that hypersonic weapons cannot match the short delivery times of ballistic missiles flying on depressed trajectories, although they exhibit a modest delivery time advantage over ballistic missiles flying minimum energy trajectories. In short, hypersonic missiles are slower than ballistic missiles over intercontinental ranges. Claims that the advent of hypersonic weaponry will reduce the time necessary for warhead delivery between, for example, the United States, Russia, and China, are false.

Currently deployed long-range ballistic missiles are not designed to maneuver during reentry, either to increase accuracy or evade defenses. However, the United States has developed and tested several maneuvering reentry vehicles (MaRVs), which could be deployed on existing ballistic missiles.[48] Use of a lifting reentry body on a ballistic missile to enable maneuvering in the terminal phase, as the hypersonic glider does, would reduce delivery times slightly. For example, we find that a lifting reentry vehicle with $L/D = 1$, which is achievable using a simple biconic geometry, would reduce the depressed trajectory delivery time by approximately one-quarter to one-half of a minute, depending on range.[49]

Flight speed in the terminal phase influences the vulnerability of a missile to interception by defensive systems. Figure 9 compares vehicle velocities as a function of altitude shortly before impact at two total ranges: 6,100 km and 8,600 km (corresponding to 3,000 km and 5,500 km glide in the hypersonic case).[50]

The hypersonic vehicle, because it has been slowed by drag throughout its glide phase, begins the terminal phase at a lower velocity than either

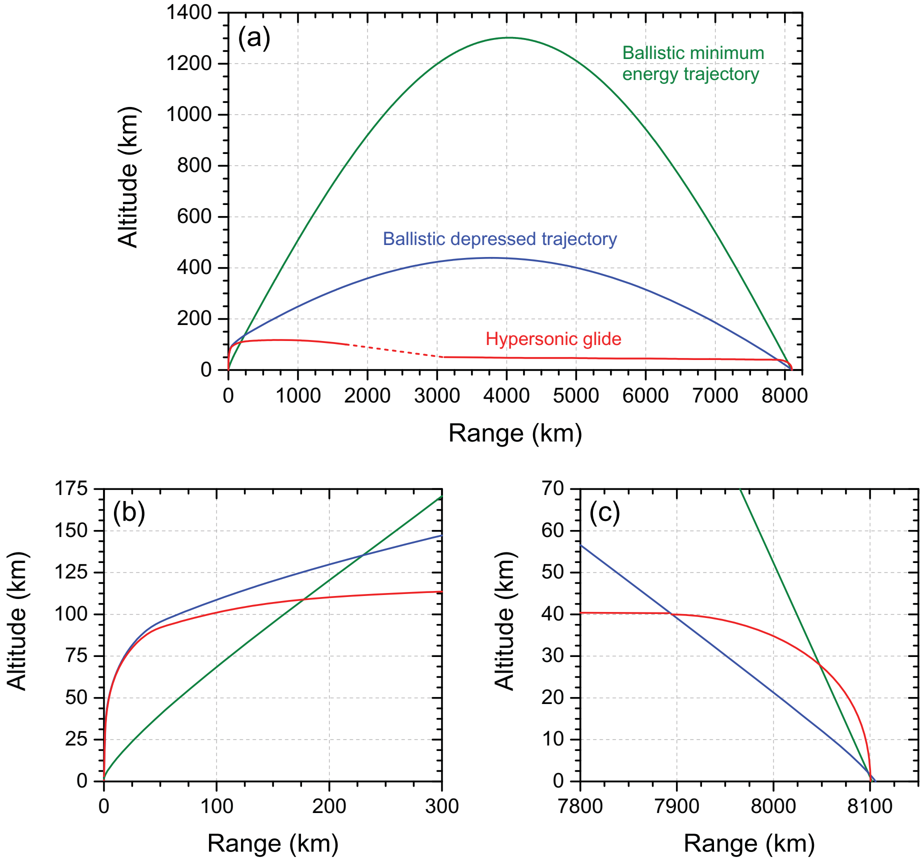

Figure 7. Calculated flight paths of a hypersonic glider and a ballistic missile flying minimum energy and depressed trajectories, fired at a target 8,100 km down-range. All missiles use identical Minotaur IV boosters. The hypersonic and ballistic depressed trajectory launches use similar boost phase trajectories based on those used in HTV-2 flight tests. The dashed section of the hypersonic curve represents analytic results rather than detailed modeling. Part (a) shows the total flight paths, while parts (b) and (c) show details of the boost and terminal phases at the start and end of missile flight. The hypersonic and depressed trajectory missiles make relatively sharp turns toward the down-range direction during the boost phase, and the depressed trajectory vehicle reenters the atmosphere at a relatively shallow angle.

ballistic missile. However, it maintains much of its speed throughout this phase via a highly efficient inverted dive maneuver, which puts it on a steep trajectory through the dense lower atmosphere (Figure 7(c)). In the ballistic minimum energy trajectory, the reentry vehicle approaches its target at a similarly steep angle and, due to its higher velocity at the start of the terminal phase, travels faster than the hypersonic glider for most or all of this phase.

The depressed trajectory ballistic missile reenters the atmosphere at a shallow angle relative to the minimum-energy trajectory case, increasing the amount of time it spends traversing the atmosphere and enhancing the

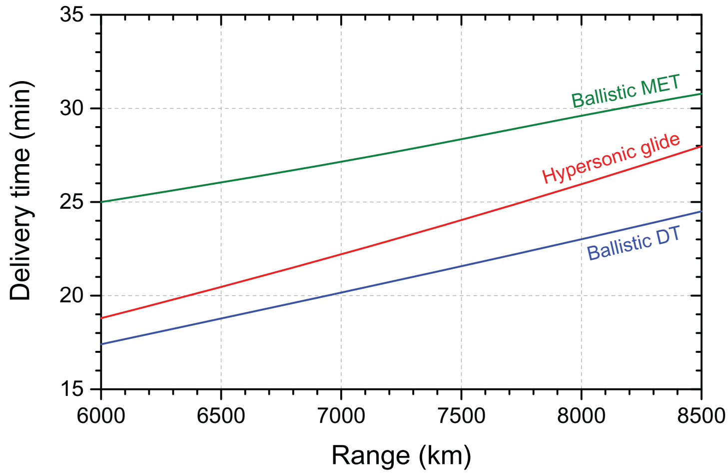

Figure 8. Calculated total delivery times for a hypersonic missile and a ballistic missile flying both minimum energy and depressed trajectories. Delivery times include boost, ballistic, reentry, pull-up, glide, and terminal phases, where applicable. Ballistic missiles fired on depressed trajectories reach their targets most quickly. Their delivery time advantage over hypersonic gliders increases with range.

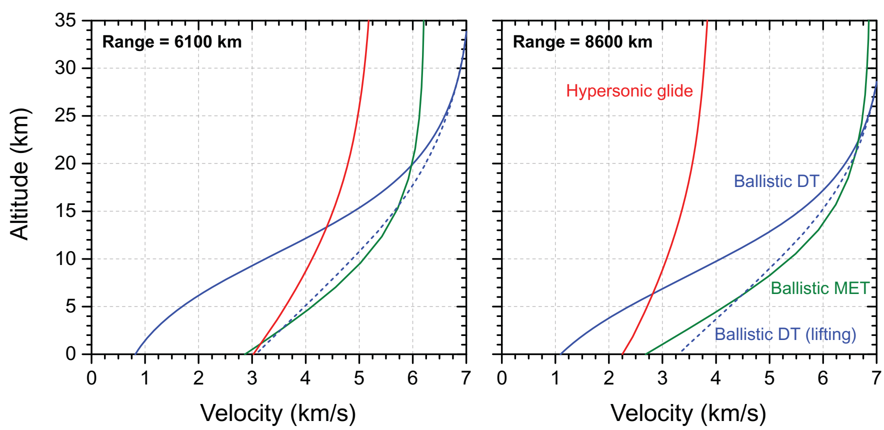

Figure 9. Terminal phase speed as a function of altitude for hypersonic gliders and ballistic reentry vehicles approaching targets at 6,100 km (left) and 8,100 km (right) ranges. The dashed line corresponds to a depressed trajectory ballistic missile armed with a lifting reentry vehicle ($L/D = 1$). For most or all of the terminal phase the hypersonic glider is slower than the ballistic missile reentry vehicles, with the exception of the ballistic depressed trajectory using a non-lifting reentry vehicle.

effects of drag. While it begins the terminal phase at a higher velocity than the hypersonic glider, it loses much of this speed by the time it approaches the target. Equipping the missile with a lifting reentry vehicle, as discussed above, would allow it to more quickly dive to the ground and to maintain speeds higher than that of the hypersonic glider throughout the terminal phase.

Detection, tracking, and early warning

In addition to their purported speed advantage, it is often claimed that hypersonic weapons can bypass existing early warning systems, further attenuating adversary response times. To be sure, their low-altitude flight significantly reduces the range at which they can be detected by ground-based radar systems compared with ballistic missiles, since Earth's curvature blocks a radar's line-of-sight to a low-flying glider at distances of more than a few hundred kilometers.[51] The formation of a high-temperature plasma sheathe around a hypersonic glider might also alter its radar cross section.[52]

However, two states at the forefront of the hypersonic arms race, the United States and Russia, do not rely solely on ground-based radar to detect missile attacks; both have fielded space-based sensors since the 1970s.[53] China is reportedly developing its own space-based early warning system with assistance from Russia.[54] These satellite-mounted IR detectors are designed to spot the bright rocket plumes produced by ballistic missile launches.

Space-based IR sensors will also detect the launch of hypersonic boost-glide weapons, since they are launched on large rockets similar to those used with ICBMs. Moreover, hypersonic glide through the atmosphere produces immense heating of glide vehicles and the surrounding air, yielding strong IR signatures that, when sufficiently intense, can be detected by space-based sensors. Thus, while hypersonic weapons might bypass some components of early warning systems, they are particularly vulnerable to others.

To quantify the visibility of hypersonic gliders to space-based IR sensors, we modeled the heating and thermal radiation of these vehicles. Figure 10 shows, as an example, the calculated temperature distribution along the centerline of the upper surface of a glider traveling at $v = 6$ km/s at its equilibrium glide altitude of $h = 49.7$ km. Our results show good agreement with prior computational fluid dynamics calculations by Niu et al.[55] For example, they report temperatures along the upper surface centerline, excluding the vehicle's rounded nose tip, in the range 2,060–1,130 K for glide at a velocity of $v = 5.4$ km/s and an altitude of $h = 60$ km. Our model predicts temperatures in the range 1,950–1,310 K under the same conditions.[56]

These surface temperatures vary with the velocity of the glider and the density of the surrounding air (Equations (8)–(10)). Figure 11 shows the temperature evolution as a function of glide range at a point on the glider centerline 1 m behind the vehicle nose.[57] These temperatures are far in excess of those experienced by ballistic missiles during their mid-course flight through outer space, which are typically below 300 K.[58]

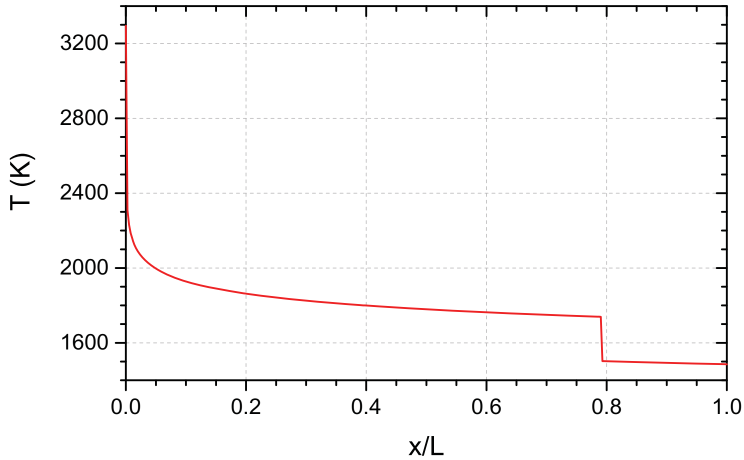

Figure 10. Calculated glider centerline temperatures as a function of fractional position along the vehicle length for flight at $v = 6$ km/s and $h = 49.7$ km. The discontinuity at $x/L \approx 0.8$ results from a change in the slope of the glider's surface (θ) at this position.

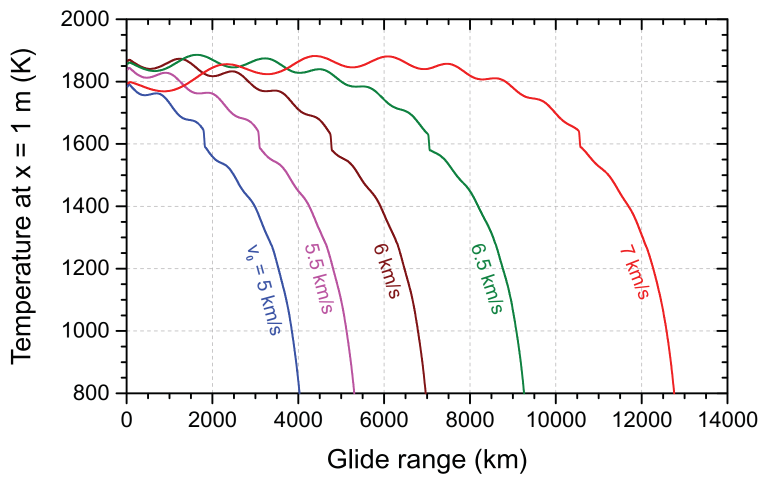

Figure 11. Glider centerline surface temperatures at a position 1 m behind the vehicle nose as a function of glide time for various initial speeds. Oscillations arise from the altitude variation shown in Figure 4. The discontinuities seen at $T \approx 1{,}600$ K are caused by the switch from Equation (9) to Equation (10) when the vehicle slows to $v \leq 4$ km/s.

These extreme temperatures give rise to intense emission of radiation in the IR spectrum. Our calculated radiance results again agree well with previously reported values. For example, Niu et al. calculated overhead radiant intensities of ~105 kW/sr in the 3–5 μm band and ~14 kW/sr in the 8–12 μm band for a vehicle traveling at $v = 5.4$ km/s at an altitude of $h = 60$ km.[59] Our model yields similar overhead radiant intensities of 113 kW/sr in the 3–5 μm band and 15 kW/sr in the 8–12 μm band for the same flight conditions.

To assess the visibility of this IR emission to early warning systems, we compared the calculated radiant intensities of a glider with the IR sensitivities of both existing U.S. space-based detection systems, using data available in the open literature. The U.S. space-based early warning system is composed of two sets of satellites: the Defense Support Program (DSP), first deployed in the 1970s, and the Space-Based Infrared System (SBIRS), currently under development with the first satellite launched in 2011.[60]

Modern DSP satellites use linear sensor arrays, ~6,000 pixels long, that rotate to cover the visible disk of Earth in 10 second intervals.[61] This yields spatial resolution on the order of 1 km and collection times on the order of 100 microseconds.[62] These sensors are tuned to a narrow wavelength band, 2.69–2.95 μm, where the atmosphere blocks most transmission of IR radiation from the Earth's surface, reducing background signal.[63] The ability of DSP satellites to observe even relatively dim, short-range missile launches was established in the 1990–1991 Gulf War, when they routinely detected launches of Iraqi Scud missiles.[64] This allows for determination of an approximate lower radiant intensity threshold for detection by DSP. Assessing the available data on Scud IR emission, Garwin and Postol place this threshold at ~20 kW/sr in the 2.69–2.95 μm band.[65]

Because hypersonic gliders are launched on large rockets, rocket plumes from these launches will be readily detectable by existing space-based sensors like the DSP. Furthermore, our results show that a hypersonic glider would emit above the threshold for reliable detection by the DSP for a substantial portion of the glide phase. Figure 12 shows calculated glider radiant intensities in the 2.69–2.95 μm band as a function of range. For example, a weapon entering glide at $v = 6$ km/s would emit above the DSP detection threshold for the first ~19 minutes of glide, corresponding to about three quarters of its maximum glide range.[66] Based on DSP's spatial and time resolution, it might conceivably provide tracking capability throughout this period, as it does for ballistic missiles.[67]

The more advanced SBIRS system could detect and track gliders for an even longer portion of glide. While relatively little information on SBIRS detection parameters is available in the open literature, a 2004 study by the American Physical Society reports technical characteristics of a notional SBIRS-like system.[68] This study assumes, based on commercially available technology at the time of its writing, that a step-stare detector operating in the short-wavelength infrared (SWIR) band (1.4–3.0 μm) with a 1 km^2 pixel footprint, 33 ms collection time, and 1 s revisit time reasonably approximates the likely performance of a SBIRS detector.[69] These parameters are generally consistent with those proposed early in the SBIRS development process.[70]

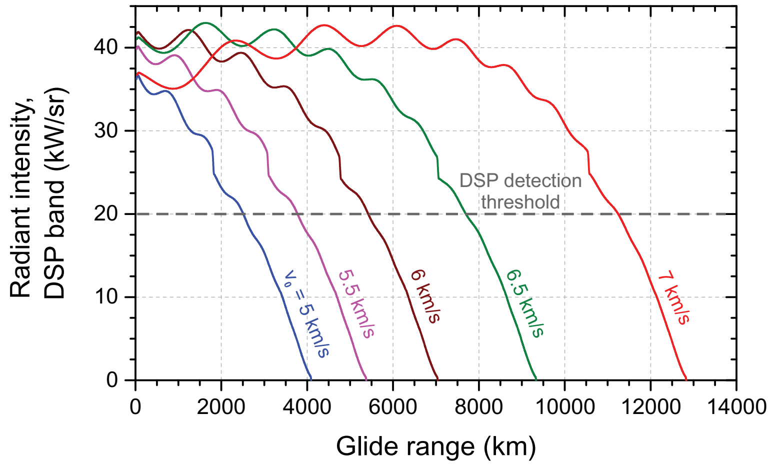

Figure 12. Glider overhead radiant intensity in the DSP detection band (2.69–2.95 μm) as a function of glide time for various initial speeds. In all cases glider radiance remains above the approximate 20 kW/sr DSP detection threshold for the majority of glide. Oscillations arise from the altitude variation shown in Figure 4. The discontinuities seen at $I \approx 25$ kW/sr are caused by the switch from Equation (9) to Equation (10) when the vehicle slows to $v \leq 4$ km/s.

Accounting for the effects of atmospheric absorption, background signal, etc., the APS study concludes that a notional SBIRS like system "could detect sources with luminosities as low as 6 kW/sr [in the SWIR band] with some margin of safety" and could determine the three dimensional position of such a source to within less than 300 m.[71] As shown in Figure 13, a hypersonic glider emits above this detection threshold for essentially the entirety of glide.[72] This further indicates that hypersonic missiles can be detected by existing space-based sensor technologies. Moreover, given the predicted spatial precision of the SBIRS system and its short revisit time, tracking hypersonic gliders through most of their flight is likely feasible.

While hypersonic missiles will remain visible to space-based sensors throughout much of their glide phase, for sufficiently long flights there might exist short periods near the end of glide when the vehicle has slowed enough that its radiant intensity drops below the threshold for detection. For our model, the overhead radiant intensity drops below the SBIRS detection threshold when the glider slows to $v = 1.6$ km/s (around 26 km altitude) and below the DSP threshold when it slows to $v = 3.5$ km/s (around 37 km altitude). Even with precise tracking up to this point, there could remain a degree of uncertainty in the missile's subsequent trajectory and its ultimate target. Still, this post-detection maneuvering will be strictly limited by the reduced velocity of the vehicle at this stage. Figure 14 illustrates the calculated maximum achievable cross-range travel of a glider if

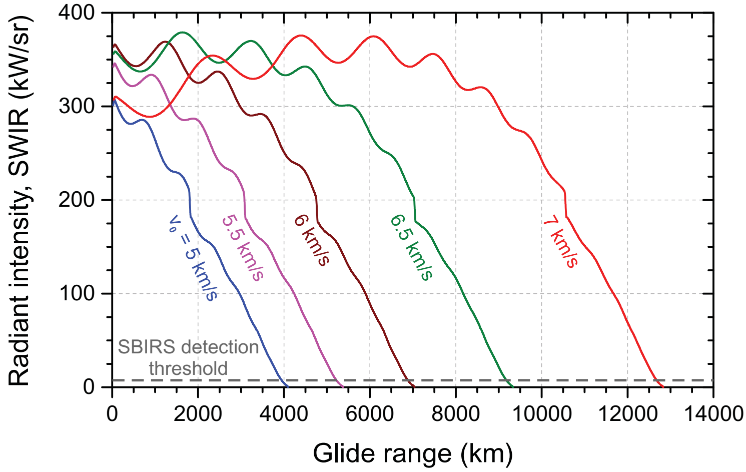

Figure 13. Glider overhead radiant intensity in the SWIR band (1.4–3.0 μm) as a function of glide time for various initial speeds. In all cases glider radiance remains above the approximate 6 kW/sr SBIRS detection threshold for essentially the entire glide phase. Oscillations arise from the altitude variation shown in Figure 4. The discontinuities seen at $I \approx 200$ kW/sr are caused by the switch from Equation (9) to Equation (10) when the vehicle slows to $v \leq 4$ km/s.

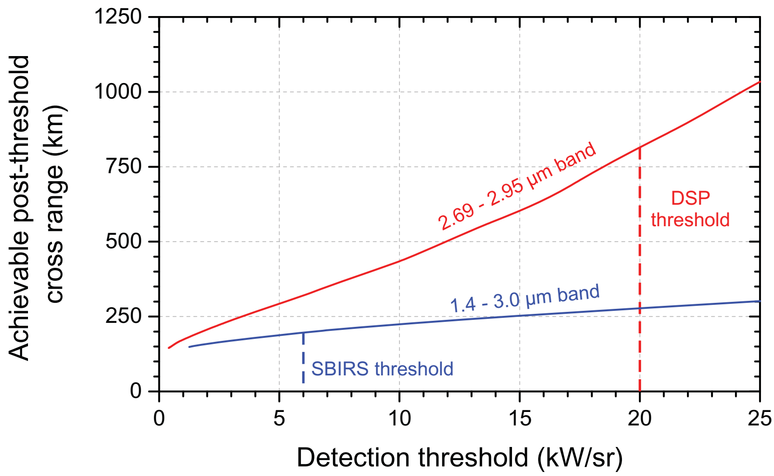

Figure 14. The maximum achievable cross-range travel of a glider assuming that maneuvering in the cross-range direction begins only once the glider's radiant intensity drops below a specific detection threshold. Data are shown for a range of detection thresholds in both the DSP detection band (2.69–2.95 μm, upper line) and the notional SBIRS detection band (1.4–3.0 μm, lower line). In both cases cross-range travel is limited to hundreds of kilometers.

maneuvering is delayed until IR emission drops below a certain detection threshold.

For the 6 kW/sr detection threshold predicted for a SBIRS-like system in the SWIR band, maximum cross-range flight of only ~200 km and down-range flight of ~400 km would be possible once a glider had slowed sufficiently to emit below this threshold (at velocities below the hypersonic regime, as shown in Figure 3). At this point, the missile would threaten a region roughly equivalent in area to Nicaragua or the U.S. state of Pennsylvania. Thus, while some targeting uncertainty would remain even after detection and tracking by space-based sensors, this uncertainty would be tightly constrained by physical limitations on the maneuvering of a missile. Furthermore, this uncertainty pertains only to detection and tracking by space-based sensors. As a glider approached to within a few hundred kilometers of its target, it would become visible to ground-based radar systems that could provide continuity of tracking.[73]

Misperceptions of hypersonic missile capabilities

This analysis demonstrates the falsity of common claims regarding the capabilities of hypersonic weapons. Computational modeling indicates that ballistic missiles fired on depressed trajectories can fly intercontinental distances significantly faster than can hypersonic boost-glide systems (Figure 8). Furthermore, its shows that hypersonic weapons are not invulnerable to detection by early warning systems but will instead remain visible to space-based sensors during launch and the majority of the glide phase. They are thus unlikely to meaningfully reduce the time available for a targeted adversary to respond.[74]

This misalignment between oft-repeated claims of hypersonic weapon performance and their apparent technical capabilities raises several questions. How did these misconceptions originate? Why have they persisted? Why are states so ardently pursuing weapon systems that do not perform as advertised? Clearly, answers to these questions are not to be found in the technical basis for hypersonic missile performance. Rather, they require analysis of the processes by which technological facts regarding hypersonic missile performance—delivery times, vulnerability to detection, etc.—have been socially constructed.[75] Here, we consider the U.S. hypersonic program as a representative case.

The social construction of technical facts

U.S. hypersonic missile development is led by the Department of Defense (DOD), which currently oversees at least six distinct programs spread across the military services and DARPA.[76] As shown in the modeling results reported here, many of the justifications the DOD has offered for hypersonic weapon development, based on their purportedly revolutionary capabilities, do not hold up to technical scrutiny. Furthermore, several analysts have concluded that DOD planning in this area appears only weakly tied to any specific military mission or objective.[77] This suggests that factors unrelated to missile performance may be driving development.

The unique organizational predilections of the DOD illuminate several possible factors. For example, Allison and Zelikow identify in DOD behavior "effective imperatives to avoid … inferiority to an enemy weapon of any class" or "a decrease in dollars budgeted."[78] Both driving forces for weapon development are independent of technical performance parameters. Instead, they incentivize the pursuit of weapons that match those under development by adversaries and that present opportunities for the capture of budgetary resources—descriptions clearly applicable to hypersonic weapons.[79]

Yet while the DOD's pursuit of a missile technology may be only weakly tied to technical capabilities, social conceptions of missile performance play a key role in the marshaling of external support for weapons development. The DOD alone cannot establish and carry out a missile development program; it must enroll the support of others with different, potentially conflicting organizational interests, such as congressional appropriators.

In their sociological studies of U.S. ballistic missile development programs, MacKenzie and Spinardi show that this dynamic, in which proponents of new missile technologies enroll the support of skeptical actors external to their organizational unit, is typical of weapons development efforts and begets particular social processes by which technical facts regarding missile performance are socially constructed.[80] In these processes, development of a new missile technology is not "a matter of engineering just metal, wires, and equations. People [have] to be engineered, too."[81] Success requires the engineering of a sociotechnical ensemble that "includes both gyroscopes and Senators, and if one is seen not to work as intended, the other may not either."[82] DOD proponents of new missile technologies construct these ensembles through processes termed "heterogeneous engineering," wherein technologists develop weapons that work, in a technical sense, while simultaneously shaping social perceptions of what a "working" system entails.[83]

Establishing the credibility of technical claims regarding the advantages of a weapon system is, according to MacKenzie, a "key role" played by heterogeneous engineers.[84] To this end, they seek to construct technical facts that cast their favored technology as desirable and necessary.[85] Thus, social and organizational interests become embedded in ostensibly technical arguments. The actual technical capabilities of a weapon are often subordinated to these social factors: "whether [a missile] would actually perform to specification in a war situation is a moot point and not actually crucial to the success of the technology … what matters is that the technology succeeds as a network of interests," incorporating political, organizational, financial, and professional incentives.[86]

In the United States, the DOD has acquired broad leeway to unilaterally define the technical capabilities of hypersonic weapons. As Oelrich observes, "virtually anyone in the United States who has a solid technical understanding of hypersonic aerodynamics is working for the Defense Department, one of the national laboratories, a contractor working for Defense, or is a university researcher supported at least in part by Defense Department grants."[87] This near-monopoly on relevant technical expertise is buttressed by a permissive culture among congressional appropriators. Since they often lack the capacity for detailed technical analysis, "questions of weapons technology are largely … left to those most imbued with that particular culture," in this case DOD representatives.[88]

Analysis of the U.S. hypersonic program through this sociological lens reveals numerous examples of heterogeneous engineering on the part of DOD officials, through which erroneous claims regarding the performance of these weapons became embedded in dominant governmental, scholarly, and media discourses. Here, we examine two representative instances relevant to the issues discussed in this work—missile delivery times and visibility to space-based sensors.

Claim 1: Attenuated delivery times

It is commonly claimed that hypersonic weapons can reduce warhead delivery times by reaching their targets faster than existing ballistic missiles could. In 2019 testimony before the U.S. Senate Committee on Armed Services, the Commander of U.S. Strategic Command addressed this delivery time issue. Asked how long it would take a Russian hypersonic glide weapon to strike the United States, he responded: "it is a shorter period of time. The ballistic missile is roughly 30 minutes. A hypersonic weapon, depending on the design, could be half of that, depending on where it is launched from, the platform. It could be even less than that."[89]

This comparison between hypersonic and ballistic missiles, phrased so as to suggest that the former is intrinsically faster than the latter, is misleading. The 30-minute figure provided for a ballistic strike corresponds to a missile launched from Russia on a minimum energy trajectory.[90] A ballistic missile launched nearer to U.S. soil (e.g., from a submarine in the Pacific Ocean) would reach its target much more quickly, as would one launched on a depressed trajectory. As shown in Figure 8, a hypersonic weapon would take ~25 minutes to travel the distance between western Russia and the eastern United States, making it only slightly faster than an ICBM strike using a minimum energy trajectory, and slightly slower than an ICBM strike using a depressed trajectory. The 15-minute figure provided to

Congress corresponds to a hypersonic weapon launched much closer to U.S. soil—an example of forward basing that is equally applicable to ballistic missiles.

In this skillful demonstration of heterogeneous engineering, the delivery time of a forward-based hypersonic missile was compared with that of a ballistic missile launched from a much greater distance; this argument for the advantages of forward basing was presented to legislators as an argument for the advantages of hypersonic missile technology. The implication that a hypersonic missile could halve the time necessary to deliver a warhead between Russia and the United States—while false—subsequently permeated the U.S. discourse, fueling narratives of the revolutionary nature of these weapons.[91]

Claim 2: Evasion of early warning systems

Even if it flew no faster than a ballistic missile, a hypersonic weapon might still reduce adversary response times if it were able to bypass early warning systems. In 2020, the Under Secretary of Defense for Research and Engineering stated that hypersonic missiles are "20 times dimmer, or more, than the targets [the United States is] able to track" with its SBIRS satellites, suggesting a need for new satellite sensors.[92] The Director of the Missile Defense Agency told the Senate Committee on Armed Services that, due to this dimness, a new satellite constellation would be necessary to detect hypersonic missiles.[93]

It is true that, in its glide phase, a hypersonic vehicle will not match the >1 MW/sr IR intensity of the large rocket exhaust plumes that current space-based sensors were designed to observe.[94] But this is not a particularly relevant comparison. First, intercontinental-range hypersonic boost-glide weapons are launched on the same rockets as are ICBMs.[95] Therefore, hypersonic missile launches will not be appreciably dimmer than ICBM launches. Second, IR emissions from hypersonic gliders will remain substantial long after launch (Figure 12). The relevant comparison in this case is not the IR intensity of a glider relative to that of a ballistic missile rocket plume, as quoted by DOD officials, but rather its intensity relative to the detection and discrimination capabilities of space-based sensors. As shown in Figures 12 and 13, gliders will emit above the detection thresholds of both the SBIRS and DSP systems for much of their flight.

DOD statements comparing glider IR intensity with that of a rocket plume, rather than with the detection limits of existing space-based sensors, constitute another example of heterogeneous engineering. In promoting a misleading narrative regarding the adequacy of current detection systems for hypersonic early warning, they justify not only U.S. hypersonic weapon development but also plans for deployment of a vast new satellite network.[96] Claims regarding the purported undetectability of hypersonic weapons have subsequently been repeated in the news media, where they are presented as technical facts.[97]

Conclusions

Computational modeling of hypersonic boost-glide missiles reveals that the capabilities of these weapons are limited by fundamental physical constraints. The drag forces they encounter during low altitude glide rapidly reduce their velocity. Because hypersonic flight is characterized by tradeoffs between speed, altitude, maneuverability, etc., this deceleration severely restricts overall missile performance. Low altitude flight also produces immense heating of glider surfaces, yielding IR signatures sufficient for detection by existing space-based sensors.

These results call into question many of the purported advantages of hypersonic weapons over existing missile technologies. For instance, modeling shows that an ICBM flying a depressed trajectory could reach intercontinental targets faster than a hypersonic glider launched on the same rocket booster, with similar vulnerability to detection by space-based early warning systems. Similarly, ballistic missiles exhibit higher terminal phase velocities than hypersonic gliders. A ballistic missile equipped with a MaRV might therefore exhibit terminal phase maneuverability superior to that of a hypersonic weapon, allowing it to better evade defensive interceptors or strike mobile targets.

That said, hypersonic weapons possess some attributes or combinations of attributes distinct from those of existing missile technologies. Their maneuverability in the glide phase allows them to fly trajectories unachievable by ballistic missiles at speeds unachievable by typical cruise missiles. This would allow them to, for example, fly under the reach of missile defense systems designed to intercept reentry vehicles above the atmosphere. But, considering these modest distinctions between the capabilities of hypersonic missiles and ballistic missiles, the former would be best characterized as an evolutionary—not revolutionary—development relative to existing missile technology.

The apparent mismatch between widespread perceptions of hypersonic weapons and their actual technical capabilities can be attributed to the dominant role that proponents of these weapon systems have played in the social construction of technical facts regarding their performance. Several erroneous beliefs about hypersonic weapons—their supposed attenuation of delivery times or invulnerability to detection by existing early warning systems—can be traced to statements by DOD officials tailored to imply revolutionary capabilities and, in doing so, to justify the expenditure necessary for development and deployment of these systems.

Our findings clarify the probable performance of hypersonic missiles, while also demonstrating a need for further technical assessment. Beyond the issues explored here, there remain several unresolved questions that follow-on research might address. For example, this analysis reveals the sensitivity of hypersonic missile performance to glider aerodynamic parameters, particularly *L/D*, which determines the magnitude of the drag a glider experiences. As Acton notes, the *L/D* of the HTV-2, the glider on which much of this analysis is based, is relatively low.[98] If a higher *L/D* were achieved in future missile designs, glider performance (speed, range, etc.) would be enhanced. Yet competing factors, such as the thermal resilience of materials used in a glider's leading edges, may preclude substantially higher *L/D* values.[99] Assessment of the precise determinants of achievable *L/D* values, as well as other limitations on glider performance related to the thermal resilience of existing aeroshell materials, would provide an improved understanding of hypersonic weapon capabilities.[100]

Additional analysis of the vulnerability of hypersonic weapons to missile defenses would also be useful. Boost-glide systems could be vulnerable to boost-phase missile defenses early in flight, should those defenses be developed. During their glide and terminal phases hypersonic weapons would fly at altitudes too low for interception by defenses designed to intercept ballistic missiles above the atmosphere, such as the U.S. Ground-based Missile Defense (GMD) and ship-based Aegis systems.[101] Endoatmospheric defenses such as the U.S. Patriot and THAAD systems operate within the atmosphere, but are designed to intercept warheads from missiles with shorter ranges and slower speeds than ICBMs.[102] These systems might be capable of engaging hypersonic vehicles during the glide or terminal phases, given the relatively low speeds of gliders after extended flight (Figure 9). However, the maneuverability of a glider might prevent the current generation of defenses from successfully intercepting these targets. Future versions of these defenses might be more effective against maneuverable vehicles but would still be capable of defending only relatively small areas. The potential for hypersonic missiles to bypass missile defenses likely motivates Russian and Chinese development of hypersonic weapons as a hedge against U.S. missile defense systems, just as those countries are likely developing decoys and other countermeasures against U.S. exoatmospheric defenses.[103]

Finally, there remain several questions regarding hypersonic weapon guidance and communications. The formation of a high temperature plasma in the air surrounding a glider might hinder radio communications with external guidance references, like GPS satellites.[104] That said, the results reported here suggest that hypersonic gliders would be traveling slowly enough to preclude plasma formation during the terminal phase when guidance and communication are likely to be most important.

The modeling approach outlined here provides a basis for quantitatively addressing these, and other, unresolved questions regarding the performance of hypersonic weaponry.

Notes

1. The term "hypersonic" commonly refers to velocities greater than roughly five times the speed of sound (Mach number >5). Unique gas flow phenomena distinguish flight in this velocity regime. See John D. Anderson, *Hypersonic and High-Temperature Gas Dynamics*, 2nd ed. (Reston, VA: American Institute of Aeronautics and Astronautics, 2006), 13–23. https://doi.org/10.2514/4.861956.
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5. On Russia's fielding of the Avangard hypersonic boost-glide missile see Julian E. Barnes and David E. Sanger, "Russia Deploys Hypersonic Weapon, Potentially Renewing Arms Race," *The New York Times*, 27 December 2019. https://nytimes.com/2019/12/27/us/politics/russia-hypersonic-weapon.html. President Putin devoted a significant portion of his 2018 Address to the Russian Federal Assembly to hypersonic weapons, referring to Russia's acquisition of these missiles as "most important stage in the development of modern weapons systems." See Vladimir Putin, "Presidential Address to the Federal Assembly," 1 March, 2018, http://en.kremlin.ru/events/president/news/56957. Russian hypersonic missiles tested to date include the Avangard, the Kinzhal air-launched glide vehicle, and the Tsirkon hypersonic cruise missile. See John T. Watts, Christian Trotti, and Mark J. Massa, "Primer on Hypersonic Weapons in the Indo-Pacific Region" (Washington, DC: Atlantic Council, 2020). https://atlanticcouncil.org/wp-content/uploads/2020/08/Hypersonics-Weapons-Primer-Report.pdf

6. Steven Simon, "Hypersonic Missiles Are a Game Changer," *The New York Times*, 2 January 2020, https://nytimes.com/2020/01/02/opinion/hypersonic-missiles.html.
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14. Frank J. Regan, *Re-entry Vehicle Dynamics* (New York: American Institute of Aeronautics and Astronautics, 1984), 287.
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18. Niu et al., "Infrared Radiation Characteristics of a Hypersonic Vehicle Under Time-Varying Angles of Attack," 867.
19. Acton, "Hypersonic Boost-Glide Weapons," 205; Wright, "Research Note to Hypersonic Boost-Glide Weapons by James M. Acton," 225.
20. See, for example, E.H. Hirschel and C. Weiland, "Design of Hypersonic Flight Vehicles: Some Lessons from the Past and Future Challenges," *CEAS Space Journal* 1 (2011): 10–14, https://doi.org/10.1007/s12567-010-0004-4.
21. Ping Lu, Stephen Forbes, and Morgan Baldwin, "Gliding Guidance of High L/D Hypersonic Vehicles," AIAA Guidance, Navigation, and Control (GNC) Conference, 19–22 August 2013, Boston, MA, USA, https://doi.org/10.2514/6.2013-4648; Luhua Liu, Jianwen Zhu, Guojian Tang, and Weimin Bao, "Diving Guidance via Feedback Linearization and Sliding Mode Control," *Aerospace Science and Technology* 41 (2015): 16–23, https://doi.org/10.1016/j.ast.2014.11.014; JianHua Wang, LuHua Liu, and GuoJian Tang, "Guidance and Control System Design for Hypersonic Vehicles in Dive Phase," *Aerospace Science and Technology* 53 (2016): 47–60, https://doi.org/10.1016/j.ast.2016.03.010; Shili Tan, Humin Lei, and Tao Liu, "Optimal Maneuver Trajectory for Hypersonic Missiles in Dive Phase Using Inverted Flight," *IEEE Access* 7 (2019): 63493–63503, https://doi.org/10.1109/ACCESS.2019.2916464.
22. Shili Tan et al., "Optimal Maneuver Trajectory for Hypersonic Missiles in Dive Phase Using Inverted Flight."
23. Graham Warwick, "DARPA's HTV-2 Didn't Phone Home," *Aviation Week Network*, 24 April 2010; https://web.archive.org/web/20111117084740/http://www.aviationweek.com/aw/blogs/defense/index.jsp?plckController=Blog&plckBlogPage=BlogViewPost&newspaperUserId=27ec4a53-dcc8-42d0-bd3a-01329aef79a7&plckPostId=Blog%3a27ec4a53-dcc8-42d0-bd3a-01329aef79a7Post%3a70769585-4348-4701-889a-f02c58f38314&plckScript=blogScript&plckElementId=blogDest; Ian Sample, "Falcon HTV-2 is Lost During Bid to Become Fastest Ever Plane," *The Guardian*, 11 August

2011, https://theguardian.com/world/2011/aug/11/fastest-ever-plane-lost-during-test-flight.

24. Michael E. Tauber, Gene P. Menees, and Henry G. Adelman “Aerothermodynamics of Transatmospheric Vehicles,” *Journal of Aircraft* 24 (1987): 594–602, https://doi.org/10.2514/3.45483; See also Anderson, *Hypersonic and High Temperature Gas Dynamics*, 349–350.
25. John J. Martin, *Atmospheric Reentry* (Englewood Cliffs, NJ: Prentice-Hall, 1966), 16, 114.
26. Niu et al., “Infrared Radiation Characteristics of a Hypersonic Vehicle under Time-Varying Angles of Attack.”
27. Anderson, *Hypersonic and High Temperature Gas Dynamics*, 780–781; Prior work shows that hypersonic missiles rapidly approach thermal equilibrium under typical flight conditions, indicating that the radiative-adiabatic limit is a reasonable assumption. See S.A. van Binsbergen, B. van Zelderen, R.G. Veraar, F. Bouquet, and W.H.C. Halswijk, H.M.A. Schleijpen, “Hyperheat: a Thermal Signature Model for Super- and Hypersonic Missiles,” *Proceedings of the SPIE 10432, Target and Background Signatures III* (2017): 1043209, https://doi.org/10.1117/12.2276943.
28. Josef Stefan, “Über die Beziehung zwischen der Wärmestrahlung und der Temperatur,” *Sitzungsberichte der Mathematisch-naturwissenschaftlichen Classe der Kaiserlichen Akademie der Wissenschaften* 79 (1879): 391–428; Ludwig Boltzmann, “Ableitung des Stefan’schen Gesetzes, betreffend die Abhängigkeit der Wärmestrahlung von der Temperatur aus der electromagnetischen Lichttheorie,” *Annalen der Physik und Chemie* 258 (1884): 291–294.
29. Niu et al., “Infrared Radiation Characteristics of a Hypersonic Vehicle Under Time-Varying Angles of Attack,” 868.
30. Referring to this intense thermal radiation, Russian President Putin described the Avangard hypersonic glide vehicle as a “ball of fire.” See Vladimir Putin, “Presidential Address to the Federal Assembly,” 1 March, 2018.
31. The hot gases surrounding a glider also contribute to its IR signature, but likely to a lesser extent than thermal radiation from the vehicle itself. See William W. Kellogg and Sidney Passman, *Infrared Techniques Applied to the Detection and Interception of Intercontinental Ballistic Missiles* (Santa Monica, CA: RAND Corporation, 1955), 11–12, https://rand.org/pubs/research_memoranda/RM1572.html. Emission from this gas is neglected in the present model, yielding conservative estimates of IR emission.
32. Max Planck, “Über eine Verbesserung der Wien’schen Spectralgleichung,” *Verhandlungen der Deutschen Physikalischen Gesellschaft* 2 (1900): 202–204; Max Planck, “Zur Theorie des Gesetzes der Energieverteilung im Normalspectrum,” *Verhandlungen der Deutschen Physikalischen Gesellschaft* 2 (1900) 237–245.
33. Xiao et al., “Analysis of Infrared Radiation Characteristics and Detectability of HTV-2-like Hypersonic Gliding Aircrafts,” 9.
34. Acton, “Hypersonic Boost-Glide Weapons,” 206; See also the approximate calculation of similar initial glide velocities in U.S. National Research Council, *U.S. Conventional Prompt Global Strike: Issues for 2008 and Beyond* (Washington, DC: National Academies Press, 2008), 206–215, https://doi.org/10.17226/12061.
35. The value of lift and of *L/D* can be varied somewhat by changing the angle of attack of the glider, which is the angle between the body axis and the vehicle’s velocity.
36. On the long-standing concept of a constrained “corridor of continuous flight” for hypersonic vehicles, see E.P. Williams and Carl Gazley, *Aerodynamics for Space*

Flight (Santa Monica, CA: RAND Corporation, 1956), 14–26, https://rand.org/pubs/papers/P1256.html.

37. Acton, "Hypersonic Boost-Glide Weapons," 209.
38. Alternatively, a glider could compensate for redirection of the lift force by generating additional lift while turning. This would increase the drag it experienced in proportion to its *L*/*D*, again reducing velocity and flight altitude. On the drag or altitude penalty that accompanies glide phase maneuvering, see Oelrich, "Cool Your Jets," 38.
39. The United States, Russia, and China, the three states most ardently pursuing hypersonic weapons, have developed and stockpiled numerous ballistic missile systems. See Arms Control Association, "Worldwide Ballistic Missile Inventories," (2017), https://armscontrol.org/factsheets/missiles.
40. For details on ballistic missile trajectory modelling, see Appendix.
41. Amy Woolf, "*Conventional Prompt Global Strike and Long-Range Ballistic Missiles: Background and Issues*" (Washington, DC: Congressional Research Service, 2020), https://crsreports.congress.gov/product/pdf/R/R41464.
42. Wright, "Research Note to Hypersonic Boost-Glide Weapons by James M. Acton," 223.
43. Ibid., 225–227.
44. Acton, "Hypersonic Boost-Glide Weapons," 206.
45. On the trajectories possible for a ballistic missile strike see, for example, Lisbeth Gronlund and David Wright, "Depressed-Trajectory SLBMs: A Technical Assessment and Arms Control Possibilities," *Science and Global Security* 3 (1992): 103–110, http://scienceandglobalsecurity.org/archive/sgs03gronlund.pdf.
46. Wright, "Research Note to Hypersonic Boost-Glide Weapons by James M. Acton."
47. Hypersonic gliders and ballistic missile reentry vehicles with equal velocities and masses would possess equal kinetic energies at booster burn-out. This kinetic energy alone might be relied upon to inflict damage on a target. If, instead, both vehicles carried identical explosive warheads, the reentry vehicle would likely be significantly lighter than the glider, allowing it to achieve a higher speed at the end of its boost phase in a depressed trajectory and reducing its relative flight time to a given range. For example, a reentry vehicle carrying a single, modern nuclear warhead could have a mass of 500 kg or less; our calculations show that using this same booster, a ballistic missile flying a depressed trajectory and carrying a payload of 500 kg would have a flight time of about 21 minutes to 8,500 km, which is significantly faster than the hypersonic weapon (Figure 8). Therefore, our modelling yields conservative estimates of ballistic missile flight speeds and delivery times relative to those of hypersonic weapons.
48. Matthew Bunn, "Technology of Ballistic Missile Reentry Vehicles," in *Review of U.S. Military Research and Development: 1984*, eds. Kosta Tsipis and Penny Janeway (Mclean, VA: Pergamon, 1984), 87–107.
49. Michael D. Griffin and James R. French, *Space Vehicle Design*, 2nd ed. (Reston, VA: American Institute of Aeronautics and Astronautics, 2004), 315, https://doi.org/10.2514/4.862403.
50. A ballistic coefficient of $\beta = 12{,}200\ \mathrm{kg/m^2}$ is assumed for the ICBM reentry vehicle. This agrees with approximate figures quoted for modern ICBMs. See Bunn, "Technology of Ballistic Missile Reentry Vehicles," 71.
51. James M. Acton, *Silver Bullet? Asking the Right Questions About Conventional Prompt Global Strike* (Washington, DC: Carnegie Endowment for International

Peace, 2013), 157, https://carnegieendowment.org/files/cpgs.pdf. Over-the-horizon radar systems, which take advantage of refraction or diffraction effects to probe beyond their line of sight, are an exception.

52. See, for example, John W. Marini, *On the Decrease of the Radar Cross Section of the Apollo Command Module due to Reentry Plasma Effects* (Greenbelt, MD: National Aeronautics and Space Administration, 1967), https://ntrs.nasa.gov/citations/19670020821.
53. See Pavel Podvig, "History and the Current Status of the Russian Early-Warning System," "*Science and Global Security*" 10 (2002): 21–60, http://scienceandglobalsecurity.org/archive/sgs10podvig.pdf; Jeffrey T. Richelson, "*America's Space Sentinels: The History of the DSP and SBIRS Satellite Systems*" (Lawrence, KS: University Press of Kansas, 2018), https://doi.org/10.2307/j.ctv7h0trq.
54. U.S. Department of Defense, Office of the Secretary of Defense, *Military and Security Developments Involving the People's Republic of China* (2020), 89, https://media.defense.gov/2020/Sep/01/2002488689/-1/-1/1/2020-dod-china-military-power-report-final.pdf; Dmitry Stefanovich, "Russia to Help China Develop an Early Warning System," *The Diplomat*, 25 October 2019, https://thediplomat.com/2019/10/russia-to-help-china-develop-an-early-warning-system/.
55. Niu et al., "Infrared Radiation Characteristics of a Hypersonic Vehicle Under Time-Varying Angles of Attack," 870.
56. Our modelling predicts stagnation point temperatures higher than those reported in Niu et al., "Infrared Radiation Characteristics of a Hypersonic Vehicle Under Time-Varying Angles of Attack." They calculate a stagnation point temperature of ∼2200 K, compared with ∼3300 K calculated here. However, since the stagnation point constitutes only a small portion of the glider surface area, this difference has little effect on the total vehicle IR light emission.
57. While we use the results of these heating calculations to estimate infrared emission from hypersonic gliders, they also constitute a basis for calculating heating of the interior of a glider, and of the necessary thermal protection. For analysis of these aspects of hypersonic missile performance see David Wright, "Heat Conduction into a Hypersonic Glide Vehicle," 2020, https://lnsp.mit.edu/s/Wright-Heat-conduction-into-a-hypersonic-glide-vehicle_11-12-20.pdf.
58. Wilton Park, *Missile Defence, Deterrence and Arms Control: Contradictory Aims or Compatible Goals?* (Geneva: United Nations Institute for Disarmament Research, 2002), 6, https://unidir.org/publication/missile-defence-deterrence-and-arms-control-contradictory-aims-or-compatible-goals.
59. Niu et al., "Infrared Radiation Characteristics of a Hypersonic Vehicle Under Time-Varying Angles of Attack," 870.
60. Richelson, "*America's Space Sentinels*".
61. Geoffrey Forden, Pavel Podvig, and Theodore A. Postol, "False Alarm, Nuclear Danger," *IEEE Spectrum* 37 (2000): 38, https://doi.org/10.1109/6.825657. Early DSP satellite used 2000 pixel arrays. See Ellis E. Lapin, "Surveillance by Satellite," *Journal of Defense Research* 8 (1976): 173, https://nsarchive2.gwu.edu/NSAEBB/NSAEBB235/13.pdf.
62. Ibid., 176.
63. Ibid., 171.
64. Richelson, *America's Space Sentinels*, 157–176. The performance of DSP in this tactical mission, far beyond the system's design parameters, was touted as "an outstanding success." See United States Space Command, *Operations Desert Shield*

and Desert Storm Assessment (1992), 20, https://nsarchive2.gwu.edu/NSAEBB/NSAEBB39/document10.pdf.

65. Richard L. Garwin and Theodore A. Postol, "Airborne Patrol to Destroy DPRK ICBMs in Powered Flight" (2017): 26–40, https://fas.org/rlg/airborne.pdf.
66. As previously discussed, these figures correspond to observation of the glider from directly overhead. Observation from alternate viewing angles (as determined by the positions of satellites in a sensor constellation relative to the glider trajectory) would increase or decrease the observed intensity in proportion to the corresponding change in the observed area of the vehicle. For a quantitative analysis of observed intensity as a function of viewing angle see Niu et al., "Infrared Radiation Characteristics of a Hypersonic Vehicle Under Time-Varying Angles of Attack," 870. The DSP constellation consists of satellites in geosynchronous Earth orbit, providing near-overhead viewing angles for objects flying near Earth's equator and less ideal viewing angles for objects flying near Earth's poles. For these sensors, the observed IR signature of a glider flying near one of the poles might be reduced by up to approximately 50% relative to those shown in Figure 12, such that tracking by DSP sensors might be temporarily hindered until the glider returned to lower latitudes.
67. The DSP tracks ballistic missiles through a process of "discrimination between noise and 'real' signals; of search for further subsequent (in time) real signals in the geographical vicinity of that signal initiating the process; of assembly of collections of observations into tentative tracks; of testing of these tracks against analytical and pragmatic criteria; and upon establishment of validity, of determination of the launch coordinates, direction, time, and type of missile." See Lapin, "Surveillance by Satellite," 179.
68. David K. Barton et al., "Report of the American Physical Society Study Group on Boost-Phase Intercept Systems for National Missile Defense: Scientific And Technical Issues," *Reviews of Modern Physics* 76 (2004): s159–s170, https://doi.org/10.1103/RevModPhys.76.S1.
69. Ibid., s167.
70. See, for example, "Report of the Space-Based IR Sensors/Technical Support Group," (October 1993), 13–15, https://nsarchive2.gwu.edu/NSAEBB/NSAEBB235/37.pdf. Here, a 4 km^2 pixel footprint and a collection time of a few ms were quoted.
71. Barton et al., "Report of the American Physical Society Study Group on Boost-Phase Intercept Systems for National Missile Defense," s168. Atmospheric attenuation has a minor effect on IR transmission to satellites from typical hypersonic flight altitudes, which are significantly higher than the altitudes at which clouds form.
72. The SBIRS constellation consists of satellites in both geosynchronous Earth orbit (providing near-overhead viewing angles of objects near the equator) and highly elliptical orbits (providing near-overhead viewing angles of objects at high latitudes). Thus, the observed IR signature data shown in Figure 13 will be only weakly sensitive to glider position on Earth; significant attenuation of this signal due to suboptimal viewing angles is unlikely.
73. Acton, *Silver Bullet?*, 157.
74. The ability of hypersonic gliders to avoid some types of missile defenses may also provide a motivation for Russia and China to acquire these systems in response to U.S. development of missile defenses. This is a concern for U.S. planners, but is not a motivation for the United States to develop long-range boost-glide vehicles, since it has already developed maneuvering warheads for use with its ballistic missiles and its adversaries are not developing advanced defenses against long-range missiles. U.S.

development of shorter-range hypersonic systems may be motivated by the possibility of bypassing theater-scale defenses. We discuss the missile defense issue in more detail in the final section of this article.

75. This analysis draws from a large literature on the sociology of technology. For an overview, see Wiebe E. Bijker, Thomas P. Hughes, and Trevor Pinch, eds., *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, anniv. ed. (Cambridge, MA: MIT Press, 2012).
76. Kelley Sayler, *Hypersonic Weapons: Background and Issues for Congress* (Washington, DC: Congressional Research Service, 2020), 4–5.
77. See, for example, John Borrie, Amy Dowler, and Pavel Podvig, *Hypersonic Weapons: A Challenge and Opportunity for Strategic Arms Control* (New York: United Nations Office for Disarmament Affairs, 2019), 15, https://un.org/disarmament/wp-content/uploads/2019/02/hypersonic-weapons-study.pdf; Acton, *Silver Bullet?*, 9–29.
78. Graham Allison and Philip Zelikow, *Essence of Decision: Explaining the Cuban Missile Crisis*, 2nd ed. (New York: Addison-Wesley, 1999), 169. U.S. officials commonly cite Chinese and Russian development of hypersonic weapons as a primary rationale for U.S. acquisition of these missiles. See, for example, statements by then Undersecretary of Defense for Research and Engineering Michael Griffin and then DARPA director Steven Walker, as quoted in Ben Brimelow, "Pentagon Warns that the US is Falling Behind to China in Hypersonic Missile Race," *Business Insider*, 20 April 2018, https://businessinsider.com/us-falling-behind-to-china-hypersonic-missile-race-2018-4; Patrick Tucker, "The US is Accelerating Development of its own 'Invincible' Hypersonic Weapons," *Defense One*, 2 March 2018, https://defenseone.com/technology/2018/03/united-states-accelerating-development-its-own-invincible-hypersonic-weapons/146355/.
79. Similar organizational dynamics have been identified in prior DOD missile development efforts. See, for example, Spinardi's analysis of the fleet ballistic missile program, wherein missile development ostensibly motivated by a need to counter Soviet missile defenses yielded systems that were "premature, excessive, or completely inappropriate." Graham Spinardi, *From Polaris to Trident: The Development of US Fleet Ballistic Missile Technology* (Cambridge: Cambridge University Press, 1994) 66–74, 175, https://doi.org/10.1017/cbo9780511559136.
80. Donald MacKenzie, "*Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance*" (Cambridge, MA: MIT Press, 1990); Spinardi, *From Polaris to Trident*.
81. MacKenzie, *Inventing Accuracy*, 28.
82. Spinardi, *From Polaris to Trident*, 192.
83. See ibid., 15–18, 173, 190–193. The concept of heterogeneous engineering was first developed in John Law, "Technology and Heterogeneous Engineering: The Case of Portuguese Expansion," in *The Social Construction of Technological Systems*, eds. Bijker, Hughes, and Pinch, 111–134. See also Hughes's related concept of "system builders" who simultaneously manipulate technical, social, political, and financial systems to guide technological change; Thomas Parker Hughes, *Networks of Power: Electrification in Western Society, 1880–1930* (Baltimore: John Hopkins University Press, 1983).
84. MacKenzie, *Inventing Accuracy*, 93. On the social construction of technical facts see also Trevor J. Pinch and Wiebe E. Bijker, "The Social Construction of Facts and Artefacts: or How the Sociology of Science and the Sociology of Technology might Benefit Each Other," *Social Studies of Science* 14 (1984): 399–441, https://doi.org/10.1177%2F030631284014003004.

85. In accordance with the sociological literature, we use the term "fact" to refer to knowledge-claims that have acquired widespread acceptance as accurate representations of hypersonic missile performance, regardless of their veracity. See, for example, ibid.
86. Spinardi, *From Polaris to Trident*, 17.
87. Ivan Oelrich, "Hypersonic Missiles: Three Questions Every Reader Should Ask," *Bulletin of the Atomic Scientists*, 17 December 2019, https://thebulletin.org/2019/12/hypersonic-missiles-three-questions-every-reader-should-ask/.
88. Spinardi, *From Polaris to Trident*, 194.
89. U.S. Senate, Committee on Armed Services, "*Hearing to Receive Testimony on United States Strategic Command and United States Northern Command in Review of the Defense Authorization Request for Fiscal Year 2020 and the Future Years Defense Program*" (Washington, DC: Alderson Court Reporting, 2019), 36, https://armed-services.senate.gov/imo/media/doc/19-14_02-26-19.pdf.
90. See Pavel Podvig, "Reducing the Risk of an Accidental Launch," *Science and Global Security* 14 (2006): 84, http://scienceandglobalsecurity.org/archive/sgs14podvig.pdf.
91. See, for example, Mark B. Schneider, "Russian Hypersonic Missiles Have 1 Goal (And They Might Be Unstoppable)," *The National Interest*, 11 September 2019, https://nationalinterest.org/blog/buzz/russian-hypersonic-missiles-have-1-goal-and-they-might-be-unstoppable-79591; Henry Meyer and Jake Rudnitsky, "Putin's Hypersonic Nuclear Missile Stirs Fears of Arms Race," *Bloomberg*, December 30, 2019, https://bloomberg.com/news/articles/2019-12-30/putin-s-hypersonic-nuclear-missile-stirs-fears-of-new-arms-race.
92. Quoted in John A. Tirpak, "Griffin: America Needs to Adjust to Reality of Great Power Competition," *Air Force Magazine*, 5 March 2020, https://airforcemag.com/griffin-america-needs-to-adjust-to-reality-of-great-power-competition/.
93. U.S. Senate, Armed Services Committee, "*Unclassified Statement of Lieutenant General Samuel A. Greaves, USAF, Director, Missile Defense Agency, Before the Senate Armed Service Committee Subcommittee on Strategic Forces*", 3 April 2019, 21, https://armed-services.senate.gov/imo/media/doc/Greaves_04-03-19.pdf.
94. Barton et al., "Report of the American Physical Society Study Group on Boost-Phase Intercept Systems for National Missile Defense," s161.
95. For instance, HTV-2 tests were conducted on modified Peacekeeper ICBMs. See Woolf, "Conventional Prompt Global Strike and Long-Range Ballistic Missiles," 13. Russia's Avangard hypersonic missile is mounted on retrofitted SS-19 ICBM rockets. See Franz-Stefan Gady, "Russia's Avangard Hypersonic Warhead Officially Enters Service," *The Diplomat*, 27 December 2019, https://thediplomat.com/2019/12/russias-avangard-hypersonic-warhead-officially-enters-service/.
96. Loren Thompson, "To Defeat Hypersonic Weapons, Pentagon Aims To Build Vast Space Sensor Layer," *Forbes*, 4 February 2020, https://forbes.com/sites/lorenthompson/2020/02/04/space-sensor-layer-is-the-pentagons-next-tech-mega-project/.
97. See, for example, Nathan Strout, "Who Will Help Track Hypersonic Threats from Space?" *Defense News*, 31 October 2019, https://www.c4isrnet.com/battlefield-tech/space/2019/10/31/who-will-help-track-hypersonic-threats-from-space/; Smith, "Hypersonic Missiles Are Unstoppable."
98. Acton, "Hypersonic Boost-Glide Weapons," 210–211.
99. See Shi et al., "Aerodynamic Force and Heating Optimization of HTV-2 Typed Vehicle."

100. On materials challenges associated with hypersonic flight, see D.M. van Wie, D.G. Drewry Jr., D.E. King, and C.M. Hudson, "The Hypersonic Environment: Required Operating Conditions and Design Challenges," *Journal of Materials Science* 39 (2004): 5915–5924, https://doi.org/10.1023/B:JMSC.0000041688.68135.8b.
101. On exoatmospheric ballistic missile defense, see David Hafemeister, *Nuclear Proliferation and Terrorism in the Post-9/11 World* (Cham: Springer, 2016), 121–136, https://doi.org/10.1007/978-3-319-25367-1.
102. The exception is the nuclear-tipped short-range 53T6 "Gazelle" system deployed around Moscow.
103. On the efficacy of countermeasures against missile defenses see Andrew M. Sessler et al., *Countermeasures* (Cambridge, MA: Union of Concerned Scientists and MIT Security Studies Program, 2000), https://ucsusa.org/sites/default/files/2019-09/countermeasures.pdf.
104. See, for example, Eric D. Gillman, John E. Foster, and Isaiah M. Blankson, "Review of Leading Approaches for Mitigating Hypersonic Vehicle Communications Blackout and a Method of Ceramic Particulate Injection Via Cathode Spot Arcs for Blackout Mitigation" (Cleveland, OH: National Aeronautics and Space Administration, 2010), https://ntrs.nasa.gov/citations/20100008938. Plasma sheathing has hindered terminal phase guidance in testing of maneuverable reentry vehicles, a technology closely related to hypersonic missiles. See, for example, U.S. National Research Council, *U.S. Conventional Prompt Global Strike*, 121.
105. Lisbeth Gronlund and David Wright, "Depressed-Trajectory SLBMs: A Technical Assessment and Arms Control Possibilities," *Science and Global Security* 3 (1992): 101–159.
106. David Wright, "Research Note to Hypersonic Boost-Glide Weapons by James M. Acton".
107. Frank J. Regan, *Re-entry Vehicle Dynamics* (New York: American Institute of Aeronautics and Astronautics, 1984), 287.
108. National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, and United States Air Force, *U.S. Standard Atmosphere, 1976* (Washington, DC: United States Government Printing Office, 1976), https://ntrs.nasa.gov/citations/19770009539.

Appendix. Calculating ballistic missile trajectories

We calculate the boost and ballistic phase trajectories of hypersonic missiles and the complete trajectories of ballistic missiles using a computational model that integrates the equations of motion on a round, non-rotating Earth with a realistic atmosphere, considering thrust, drag, and gravity.[105]

Since the HTV-2 glide vehicle considered in this analysis was launched on a Minotaur IV rocket booster in flight testing, we developed a model of this booster and used it to calculate both the early trajectory of the hypersonic missile and the delivery trajectories and times of ballistic missiles delivering warheads to the same range as the hypersonic vehicle. We used this booster model to simulate missiles on both minimum-energy trajectories (MET) and depressed trajectories (DT) to various ranges. Details of the Minotaur model and the trajectory used for the HTV-2 vehicle are discussed in detail elsewhere.[106]

The equations of motion over a round, non-rotating Earth with a realistic atmosphere are given below.[107]

$$\frac{dv}{dt} = \frac{T}{m}\cos\eta - \frac{C_d A}{2m}\rho v^2 - g\sin\gamma \quad (1)$$

$$\frac{d\gamma}{dt} = \frac{v\cos\gamma}{r_e + h} + \frac{T}{vm}\sin\eta - \frac{g}{v}\cos\gamma \quad (2)$$

$$\frac{d\Psi}{dt} = \frac{v\cos\gamma}{r_e + h} \quad (3)$$

$$\frac{dh}{dt} = v\sin\gamma \quad (4)$$

were t is time, $v(t)$ is the magnitude of the velocity, $\gamma(t)$ is the angle of the velocity with respect to the local horizontal, $h(t)$ is the altitude, $m(t)$ is the mass of the missile, $T(t,h)$ is the booster thrust, $C_d(v)$ is the drag coefficient of the missile, A is the missile's maximum cross-sectional area, $\eta(t)$ is the angle of the thrust with respect to the missile body axis, $g(h)$ is the gravitational acceleration, r_e is Earth's radius, $\Psi(t)$ is the range angle of the missile around the Earth, and $\rho(h)$ is the atmospheric density. Ψr_e is the missile's range measured along the surface of Earth. The geometry is shown in Figure 2 in the main text. We integrate these equations of motion over time using the midpoint method (second-order Runge-Kutta), modeling atmospheric density using the 1976 U.S. Standard Atmosphere.[108]

Thrust of a missile stage is given by:

$$T = g_0 I_{sp} \frac{dm}{dt} \quad (5)$$

where g_0 is the gravitational acceleration at the Earth's surface, and for each stage I_{sp} is the specific impulse and dm/dt is the mass flow rate of the propellant through the engine. Thrust is considered constant for all stages except the first, where its change with altitude is given by:

$$T(h) = g_0 I_{sp}(SL)\frac{dm}{dt} + A_{Nozzle}\big(p(0) - p(h)\big) \quad (6)$$

where $I_{sp}(SL)$ is the sea-level specific impulse of the first stage, A_{nozzle} is the cross-sectional exit area of the engine nozzle of the first stage, and $p(h)$ is the atmospheric pressure. During reentry, the drag of a missile's reentry vehicle is characterized by the ballistic coefficient $\beta = m/(C_d\, A)$, where m, C_d, and A are the mass, drag coefficient, and cross-sectional area of the warhead, respectively.