Quantification of Hypersonic Missile Capabilities using the *Hypersonic Glide Vehicle Simulator*

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Access the *Hypersonic Glide Vehicle Simulator* at:
https://hypersonic-missile-flight-model.onrender.com/

In recent years, hypersonic weapons have garnered a great deal of interest and funding, particularly in the United States, Russia, and China.[1] These weapons are distinguished from other missile technologies by their ability to glide through the atmosphere at more than five times the speed of sound (Mach 5 or ~1.7 km/s) for substantial portions of their flight trajectories. Figure 1 illustrates a typical hypersonic missile trajectory. In its initial stage, this trajectory is identical to the launch of a ballistic missile, a type of weapon that has been widely deployed and used for decades. After brief acceleration by a rocket engine, however, a hypersonic missile trajectory diverges from that of a ballistic system, diving to lower altitudes within Earth's atmosphere then gliding the remaining distance to the target. Hypersonic cruise missiles work in a similar fashion, yet they carry airbreathing engines that provide thrust during the glide phase.[2] They typically fly at lower maximum speeds and altitudes than hypersonic boost-glide missiles.

Hypersonic missiles are subjected to aerodynamic drag as they glide through the atmosphere, which continually slows their flight.[3] However, these aerodynamic forces also offer opportunities for extending missile range, if glide begins at the end of a long ballistic phase, and for midcourse maneuvering. Unlike a typical, long-range ballistic missile, which has little capacity to maneuver after the boost phase and therefore flies a largely predictable path to its target, a hypersonic missile can take advantage of aerodynamic forces to turn left or right and pitch up or down throughout its glide phase.[4] This enhanced maneuverability comes at the cost of lower

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[1] Kelley M. Sayler, "Hypersonic weapons: Background and issues for Congress," Congressional Research Service, https://apps.dtic.mil/sti/trecms/pdf/AD1164097.pdf

[2] David Wright, Cameron L. Tracy, "Hypersonic cruise missiles," *Science & Global Security* 32, 1-3 (2024), https://doi.org/10.1080/08929882.2024.2447176

[3] Cameron L. Tracy, David Wright, "Modeling the performance of hypersonic boost-glide missiles," *Science & Global Security* 28, 3 (2020), https://doi.org/10.1080/08929882.2020.1864945

[4] Steven T. Dunham, Robert S. Wilson, "The missile threat: A taxonomy for moving beyond ballistic," Aerospace Corporation (2020), https://csps.aerospace.org/sites/default/files/2021-08/Wilson-Dunham_MissileThreat_20200826_0.pdf

average flight velocity, longer flight time, and greater expense, relative to comparable ballistic missile designs.[5] However, maneuverability could prove useful in certain missions, offering, for example, the potential to avoid overflight of a certain region or approach a target from an unexpected direction.

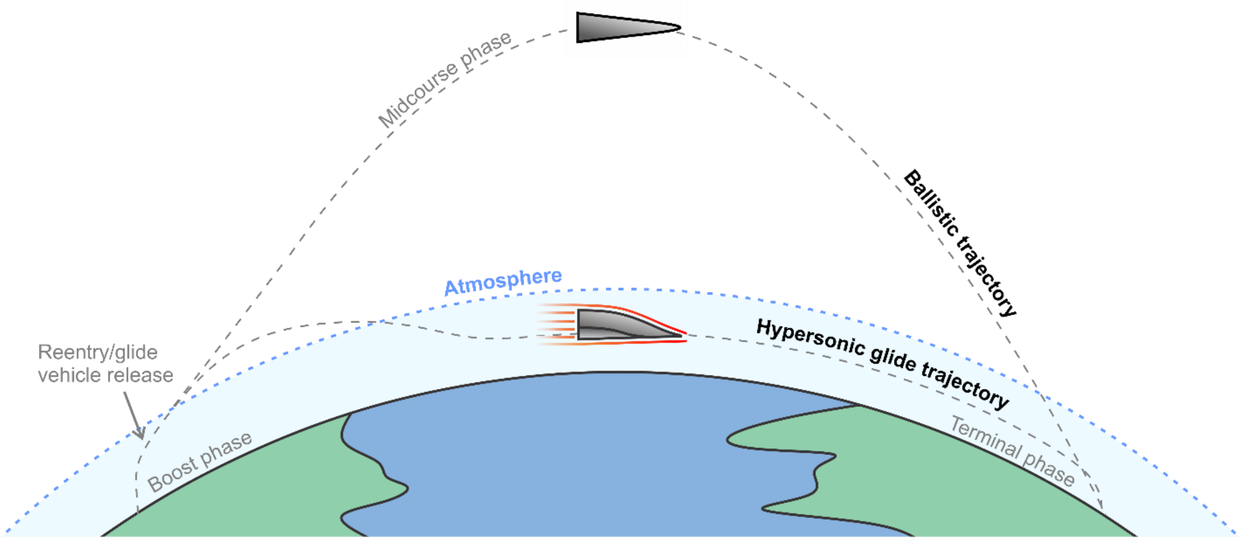

Figure 1: Schematic flight trajectories of a long-range ballistic missile, which flies an arcing path high above the atmosphere, and a hypersonic glide vehicle, which quickly dives back into the atmosphere then glides to its target.

To date, most analyses in the open literature of the performance and global security implications of hypersonic weapons are of an abstract and speculative nature. Quantitative, mission-based technical assessment is rare, and that which is available[6] often calls into question the common narrative of an impending hypersonic "revolution."[7]

To better elucidate the roles that hypersonic missiles may play in the future of war, and to anticipate their impacts on global security, technical analysis of hypersonic weapon performance

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[5] Cameron L. Tracy, David Wright, "Modeling the performance of hypersonic boost-glide missiles," *Science & Global Security* 28, 3 (2020), https://doi.org/10.1080/08929882.2020.1864945; Corinne Kramer, David Mosher, Edward G. Keating, "U.S. hypersonic weapons and alternatives," Congressional Budget Office (2023), https://www.cbo.gov/system/files/2023-01/58255-hypersonic.pdf

[6] James M. Acton, "Hypersonic boost-glide weapons," *Science & Global Security* 23, 3 (2015), https://doi.org/10.1080/08929882.2015.1087242; Cameron L. Tracy, David Wright, "Modeling the performance of hypersonic boost-glide missiles," *Science & Global Security* 28, 3 (2020), https://doi.org/10.1080/08929882.2020.1864945; David Wright, Cameron L. Tracy "Hypersonic weapons: Vulnerability to missile defenses and comparison to MaRVs," *Science & Global Security* 31, 3 (2023), https://doi.org/10.1080/08929882.2023.2270292; Corinne Kramer, David Mosher, Edward G. Keating, "U.S. hypersonic weapons and alternatives," Congressional Budget Office (2023), https://www.cbo.gov/system/files/2023-01/58255-hypersonic.pdf; David Wright, Cameron L. Tracy, "Hypersonic cruise missiles," *Science & Global Security* 32, 1-3 (2024), https://doi.org/10.1080/08929882.2024.2447176

[7] R. Jeffrey Smith, "Hypersonic missiles are unstoppable. And they're starting a new global arms race," *The New York Times*, 19 June 2019, https://www.nytimes.com/2019/06/19/magazine/hypersonic-missiles.html

in specific missions is needed. Yet this analytical work is challenging, particularly for those without technical training. Policy analysts, political scientists, and journalists, for instance, may lack the skillset necessary for modeling missile flight, and may thus rely on technically unsupported narratives in assessing the implications of hypersonic weapon development and deployment. To lower these analytical barriers, we have developed the *Hypersonic Glide Vehicle Simulator*, a web application that facilitates fast and easy computation of hypersonic missile capabilities in a variety of militarily-relevant scenarios.[8] This application makes use of computational models developed by Tracy and Wright that simulate the flight of hypersonic glide vehicles through Earth's atmosphere.[9]

Application inputs and outputs

The *Hypersonic Glide Vehicle Simulator* models the glide of a hypersonic missile through the atmosphere. This glide phase distinguishes hypersonic missile systems from more common ballistic missile systems. Simulating this phase of flight requires only a small number of user-defined inputs relating to aerodynamic properties of the glide vehicle (its ballistic coefficient and lift-to-drag ratio) and the magnitude and direction of the vehicle's velocity at the start of glide. After these inputs are provided, the application integrates six equations of motion over time, assuming a spherical, non-rotating Earth with a realistic atmosphere, using a second-order Runge-Kutta method:

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

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

$$\frac{d\eta}{dt} = \left({}^{L}\!/_{D}\right)\left(\frac{C_d A}{2m}\right)\frac{\rho v\sin\sigma}{\cos\gamma} - \frac{v\,tan\theta\,\cos\gamma\sin\eta}{r_e + h} \tag{3}$$

$$\frac{d\theta}{dt} = \frac{v\cos\gamma\cos\eta}{r_e + h} \tag{4}$$

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[8] Justin Ly, Anita Ding, David Wright, Cameron L. Tracy, *Hypersonic Glide Vehicle Simulator*, https://hypersonic-missile-flight-model.onrender.com/

[9] Cameron L. Tracy, David Wright, "Modeling the performance of hypersonic boost-glide missiles," *Science & Global Security* 28, 3 (2020), https://doi.org/10.1080/08929882.2020.1864945; David Wright, Cameron L. Tracy "Hypersonic weapons: Vulnerability to missile defenses and comparison to MaRVs," *Science & Global Security* 31, 3 (2023), https://doi.org/10.1080/08929882.2023.2270292

$$\frac{d\phi}{dt} = \frac{v\cos\gamma\sin\eta}{(r_e + h)\cos\theta} \tag{5}$$

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

where v is the vehicle's velocity, C_d is its drag coefficient, A is its effective cross-sectional area, m is its mass, ρ is atmospheric density, g is acceleration due to gravity, γ is the velocity angle measured relative to the local horizontal, r_e is Earth's radius, h is the vehicle's altitude, L/D is the vehicle's lift-to-drag ratio, σ is its roll angle, η is the velocity angle measured relative to local north, and θ and ϕ are geographic latitude and longitude coordinates. Values for atmospheric density as a function of altitude are derived from the 1976 US Standard Atmosphere model.[10] To simplify the calculations, the ballistic coefficient and L/D are assumed to be constant, neglecting variation that would occur with changes in velocity and vehicle angle of attack.

After running, the application outputs data on vehicle altitude, flight velocity, flight time, and the distance the vehicle has traveled in the downrange direction and the crossrange direction (measured perpendicular to the downrange direction). These data are provided both graphically and in tabular form, both of which can be downloaded for further analysis. The application also displays the calculated flight paths on a map projection, using user-defined geographic coordinates for the starting location and direction of glide. Finally, if requested by the user, the application calculates the geographic area threatened by the missile at the onset of the simulation, outlining the spatial extent of the glider's maneuvering capability.

User instructions

Performing calculations using the *Hypersonic Glide Vehicle Simulator* is simple. The application will automatically load upon clicking the link. This may take several minutes. Once loaded, an interface for entry of initial flight conditions and vehicle parameters appears, as shown in Figure 2. To run a simulation, the user must provide six numerical parameters (or leave them at their default values). For more complex trajectories, users can optionally provide additional parameters.

Parameter 1: initial velocity

The first, and perhaps the most important user-defined parameter is the initial glide velocity of the vehicle, given in units of kilometers per second (km/s). For a hypersonic weapon this must,

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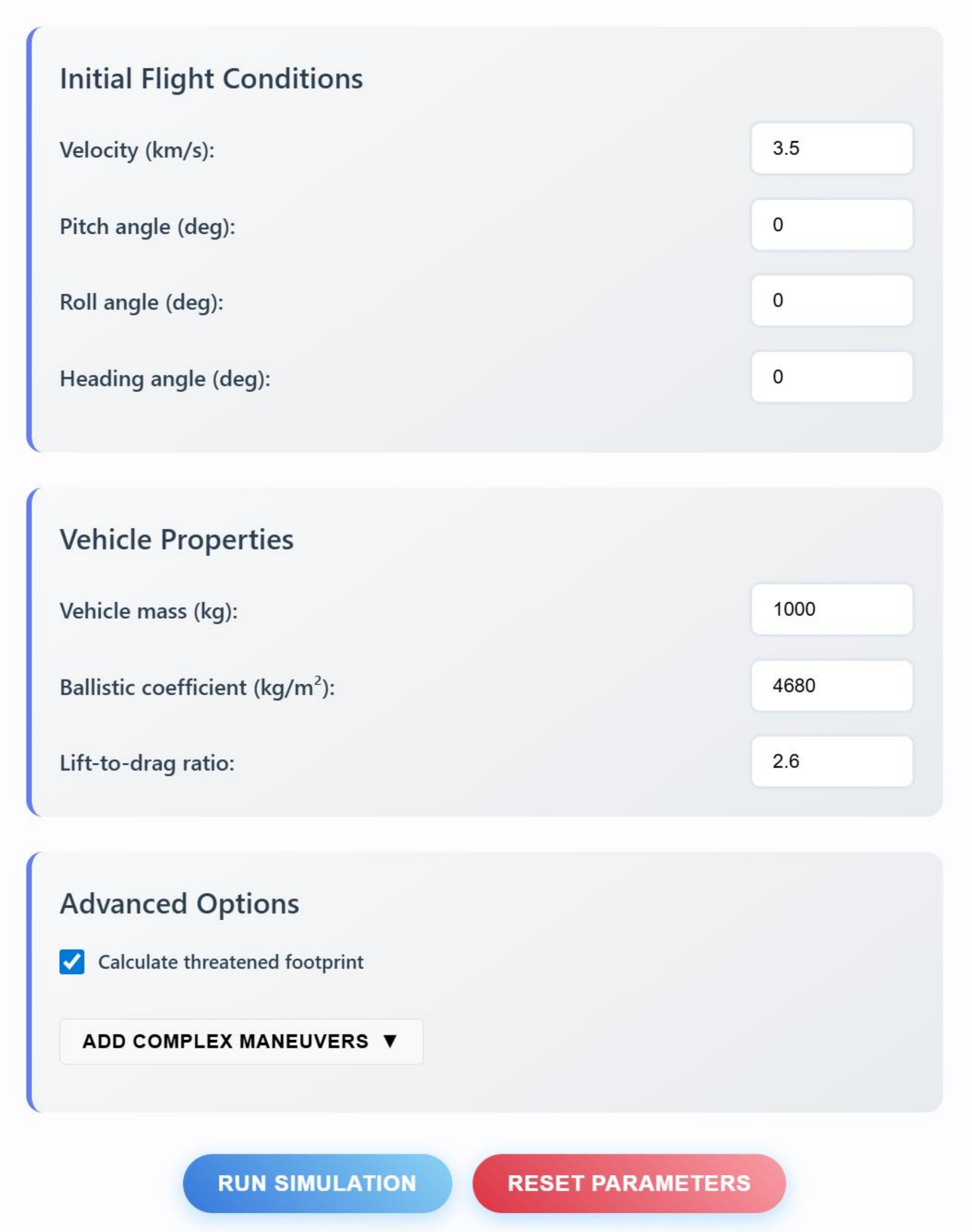
[10] National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, and United States Air Force, *U.S. Standard Atmosphere, 1976*, https://ntrs.nasa.gov/citations/19770009539

by definition, be greater than Mach 5 (~1.7 km/s). Keep in mind that the vehicle's velocity will continuously decrease from this initial value throughout glide, potentially dropping below the hypersonic threshold.



Initial Flight Conditions

Velocity (km/s): 3.5

Pitch angle (deg): 0

Roll angle (deg): 0

Heading angle (deg): 0

Vehicle Properties

Vehicle mass (kg): 1000

Ballistic coefficient (kg/m^2): 4680

Lift-to-drag ratio: 2.6

Advanced Options

☑ Calculate threatened footprint

Figure 2: The initial interface of the *Hypersonic Glide Vehicle Simulator*. Here, parameters for initial flight conditions and aerodynamic properties of a glide vehicle can be specified.

Modern intercontinental ballistic missiles (ICBMs), like the US Minuteman III, achieve maximum velocities of around Mach 23 (~7.5 km/s).[11] Since they fly primarily through outer space, in the absence of drag, they will reenter the atmosphere near their targets at approximately that velocity. That is not the case for hypersonic missiles, though they are typically launched on the same rocket boosters as are ballistic missiles, and thus achieve the same maximum velocities. At the end of a ballistic flight phase, a hypersonic vehicle will reenter the atmosphere, then execute a pull-up maneuver to initiate level glide through the atmosphere (see Figure 1). An attacker might choose to reenter the atmosphere shortly after launch or might do so later in flight in order to maximize the missile's total achievable range by gliding only after a long ballistic phase. In either case, this transition from a ballistic flight path to a glide path incurs a velocity loss, the magnitude of which will depend on particulars of the flight trajectory and the vehicle design, such as the mechanical stresses that its airframe can withstand.[12] Prior calculations and analyses of flight test data show velocity losses of roughly 10-20%.[13]

Based on the above considerations, we suggest the following process for selection of an initial velocity. First, select a booster vehicle from among the ballistic missile designs deployed by the notional attacker and determine the maximum velocity achieved by that booster (with the understanding that this will be an approximation, as the maximum velocity will vary with the mass of the payload). This might be, for example, a reported 3.6 km/s for an Iranian Emad medium-range ballistic missile (MRBM), or roughly twice that for an ICBM.[14] If information on the maximum velocity of a system is unavailable, this figure can be approximately determined from the booster's maximum range using the following equation:

$$\text{maximum velocity (km/s)} = 11 - \left(\frac{10.5}{1 + \left(\frac{R}{5355}\right)^{0.75}} \right) \tag{7}$$

where R is the maximum range of the vehicle in kilometers. The results of this equation are shown graphically in Figure 3. Note that this equation is phenomenological, and the terms have no physical meaning. Once a maximum booster velocity is determined, reduce this value by 10-20%

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[11] Center for Strategic and International Studies, "Minuteman III," https://missilethreat.csis.org/missile/minuteman-iii/

[12] James M. Acton, "Hypersonic boost-glide weapons," *Science & Global Security* 23, 3 (2015), https://doi.org/10.1080/08929882.2015.1087242

[13] 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; James M. Acton, "Hypersonic boost-glide weapons," *Science & Global Security* 23, 3 (2015), https://doi.org/10.1080/08929882.2015.1087242; David Wright, "Research note to 'Hypersonic boost-glide weapons' by James M. Acton: Analysis of the boost phase of the HTV-2 hypersonic glider tests," *Science & Global Security* 23, 3 (2015), https://doi.org/10.1080/08929882.2015.1088734

[14] Steve Fetter, David Wright, "Can the Iron Dome be transmuted into a Golden Dome?" *The Washington Quarterly* 48, 2 (2025), https://doi.org/10.1080/0163660X.2025.2514916

to account for velocity loss during the reentry and pull-up phases. Use this reduced value as the initial glide velocity.

If a user wishes to simulate flight starting after the beginning of glide—for instance, to determine the threatened footprint at a later stage of flight—one can simply run the model twice: once to determine the vehicle's velocity after a specific glide duration, then again entering this new velocity value as the initial velocity parameter.

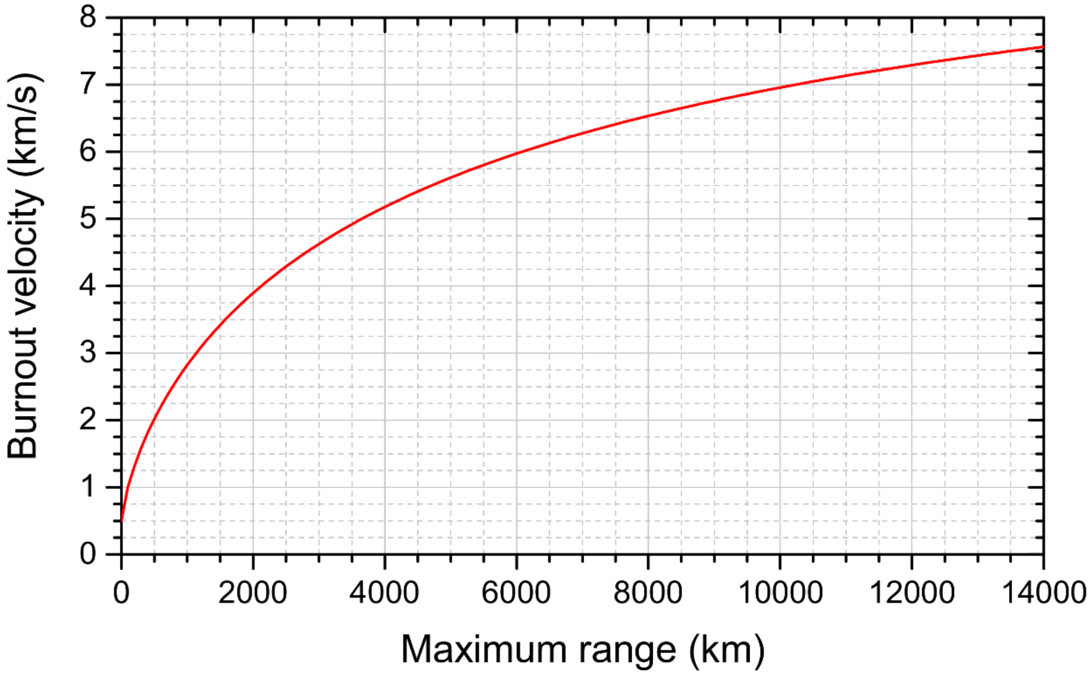

Figure 3: The approximate relationship between booster burnout speed and maximum range for a ballistic missile flying a minimum energy trajectory, absent any glide phase.

Parameters 2-4: initial vehicle orientation

The initial orientation of the vehicle, defined in three dimensions, determines the direction of both the glide velocity vector and the lift force that the vehicle generates during flight. This orientation is described by three angles for vehicle roll, pitch, and heading, each measured in degrees (°). These can be left at their default values of 0° for use cases where simulation of straight flight, solely in the downrange direction, is desired.

The roll angle is typically the most useful of these three parameters, for cases in which a user wishes to model vehicle turns. It measures rotation of the glide vehicle about an axis oriented in its direction of flight. When a vehicle adopts a nonzero roll angle, it redirects a portion of the lift force that it generates during flight away from the local vertical direction (where it counters

Earth's gravitational force) and toward a lateral direction (where it pulls the glider to the left or right).

As long as the vehicle maintains a nonzero roll angle it will turn to its left or right, with the sharpness of the turn proportional to the roll angle. Thus, for crossrange maneuvering, use of the roll angle parameter is essential. Note that executing a turn will reduce the vehicle's flight velocity and therefore its maximum achievable range. When part of the vehicle's lift force is used to turn rather than to oppose gravity, the vehicle will drop to a lower altitude where higher atmospheric density increases the lift generated, thus keeping the vehicle aloft. As a result, the vehicle also experiences greater drag than it otherwise would.

The vehicle's pitch angle is measured from the local horizontal, defined in relation to the local tangent plane at a point on Earth's surface directly below the vehicle. With a positive angle, the vehicle pitches up, such that its velocity carries it further from Earth. With a negative angle, the vehicle pitches down, toward Earth. For the most efficient, level flight path this parameter should be left at zero. Nonzero pitch angles might be useful for simulating dives of a hypersonic missile in the terminal phase of flight, or for intensifying phugoid oscillations as a glider bounces between more and less dense regions of the atmosphere.[15]

The vehicle's heading angle, also called yaw, measures rotation about a vertical axis, passing from the vehicle through a point on Earth's surface directly underneath. Changes to this parameter will change the extent to which straight flight of the vehicle (at a roll angle of 0°) will carry it in the crossrange direction, as opposed to the downrange direction.

Parameter 5: vehicle ballistic coefficient

The glide vehicle's ballistic coefficient, or mass-to-drag ratio, is an aerodynamic parameter that reflects the extent to which the vehicle's flight is slowed by atmospheric drag forces as it travels through the atmosphere. In this application, it is measured in units of kilogram-force per square meter (kg/m^2), but can also be expressed in units of pounds per square foot (lb/ft^2). This parameter has only a minor influence on many of the key model outputs, like maximum glide range or glide velocity, because changes to the ballistic coefficient are balanced by changes in the equilibrium glide altitude (and thus air density) such that the vehicle will still experience essentially the same drag force.[16] Thus, it typically has a substantial effect only on the equilibrium glide altitude of a vehicle at a particular velocity.

In their analysis of a notional vehicle design based on the Hypersonic Technology Vehicle 2 (HTV-2), a high *L*/*D*, long-range hypersonic glider that the United States flight tested twice in

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[15] N.X. Vinh, J.S. Chern, C.F. Lin, "Phugoid oscillations in optimal reentry trajectories," *Acta Astronautica* 8, 4 (1981), https://doi.org/10.1016/0094-5765(81)90001-1

[16] Cameron L. Tracy, David Wright, "'Computational fluid dynamics analysis of the infrared emission from a generic hypersonic glide vehicle'—A response," *Science & Global Security* 31, 1-2 (2023), https://doi.org/10.1080/08929882.2023.2215587

the 2010s, Candler and Leyva calculate a ballistic coefficient of 4,680 kg/m^2, assuming a vehicle mass of 1,000 kg.[17] Given that this parameter plays a relatively minor role in determination of most glider performance metrics, we suggest the use of this value for most simulations, corrected for the mass of the glider design the user wishes to simulate. This correction is simple to perform, since the ballistic coefficient is linearly proportional to glider mass. Users can use the following equation to calculate the appropriate ballistic coefficient:

$$\text{ballistic coefficient} = \left(4{,}680\ \frac{\text{kg}}{\text{m}^2}\right) \times \left(\frac{m}{1{,}000\ \text{kg}}\right) \tag{8}$$

where *m* is the mass of the glider. For an advanced, HTV-2-like design, 1,000 kg is a reasonable estimate of mass.[18] For simpler systems, usually designed for shorter flight ranges, a lower mass might be assumed. For instance, the Advanced Maneuverable Reentry Vehicle (AMaRV), a precursor to modern hypersonic glide systems that the United States flight tested several times in the late 1970s, reportedly had a much lower mass of 470 kg.[19] For a hypersonic glider with this mass, using the equation above, one could assume a ballistic coefficient of 2,200 kg/m^2.

Parameter 6: lift-to-drag ratio

The lift-to-drag ratio (*L*/*D*) reflects the balance of the two aerodynamic forces a glider experiences as it moves through the atmosphere. Lift keeps the glider aloft during flight, so long as the glider moves through the atmosphere with enough velocity to generate sufficient lift and orients that lift away from Earth. Drag, however, acts to slow the glider's flight, and thus limits glider performance.

Given that both lift and drag are critical determinants of a hypersonic missile's performance, the choice of an *L*/*D* parameter has a strong influence on the results given by this model. Vehicles with high values of *L*/*D*, often associated with slender geometries and sharp leading edges, can fly farther, maintain their speed longer, and maneuver more extensively than vehicles with lower *L*/*D* values. Note that while a real hypersonic vehicle's *L*/*D* will vary as a function of flight speed and angle of attack, this model approximates *L*/*D* as a single, constant value.

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[17] Graham V. Candler, Ivett A. Leyva, "Computational fluid dynamics analysis of the infrared emission from a generic hypersonic glide vehicle," *Science & Global Security* 30, 3 (2022), https://doi.org/10.1080/08929882.2022.2145777

[18] David Wright, "Research note to 'Hypersonic boost-glide weapons' by James M. Acton: Analysis of the boost phase of the HTV-2 hypersonic glider tests," *Science & Global Security* 23, 3 (2015), https://doi.org/10.1080/08929882.2015.1088734

[19] Gary Allen, Jr., "Composite heat shields revisited," *AIAA Meeting Papers* (1997), https://doi.org/10.2514/6.1997-471

For an advanced, long-range glide vehicle like the HTV-2, an *L*/*D* of 2.6 appears to be appropriate, based on both modeling and analysis of flight test data.[20] These vehicles tend to feature wedge-like shapes and take advantage of waverider design principles.[21] Parametric glider design calculations suggest that this value is near a functional upper limit for *L*/*D*, accounting for the need to keep heating rates of vehicle leading edges low, and that values greater than around 3 are unrealistic.[22]

Less capable systems, which may be simpler to design and cheaper to produce, often use conical geometries, as opposed to wedge-like. The Common Hypersonic Glide Body (C-HGB), a glide vehicle used in multiple US hypersonic missile designs and currently deployed as a component of the Long-Range Hypersonic Weapon, is an example of such a system.[23] For this type of glide vehicle, several analysts propose a lower *L*/*D* value of 2.2.[24] Thus, as a general guideline we recommend the use of 2.6 for long-range, wedge-shaped systems and 2.2 for other systems, in the absence of data on *L*/*D* for a specific system of interest to a user.

Advanced options

Input of the six parameters discussed above is sufficient to run the application. However, for users interested in simulating complex trajectories, two additional "advanced options" are available.

The first advanced option is used to determine the glider's threatened footprint, or the maximum extent of the geographic area that a hypersonic missile could reach if it began maneuvering at the start of the simulation.[25] If the user selects the box labeled "calculate threatened footprint" the application will simulate 19 separate flight trajectories: one flying straight in the downrange direction using the glide and vehicle parameters provided by the user, and 18 more featuring increasingly sharp turns to the glider's left and right, resulting from increasing glider roll angles. In all simulations, once the glider's flight is perpendicular to its initial flight direction its

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[20] Graham V. Candler, Ivett A. Leyva, "Computational fluid dynamics analysis of the infrared emission from a generic hypersonic glide vehicle," *Science & Global Security* 30, 3 (2022), https://doi.org/10.1080/08929882.2022.2145777; James M. Acton, "Hypersonic boost-glide weapons," *Science & Global Security* 23, 3 (2015), https://doi.org/10.1080/08929882.2015.1087242

[21] Feng Ding, Jun Liu, Chi-bing Shen, Zhen Liu, Shao-hua Chen, Xiang Fu, "An overview of research on waverider design methodology," *Acta Astronautica* 140 (2017), https://doi.org/10.1016/j.actaastro.2017.08.027

[22] Jiatong Shi, Liang Zhang, Baosen Jiang, Bangcheng Ai, "Aerodynamic force and heating optimization of HTV-2 typed vehicle," 21st AIAA International Space Planes and Hypersonics Technologies Conference (2017), https://doi.org/10.2514/6.2017-2374

[23] Andrew Feickert, "The U.S. Army's Long-Range Hypersonic Weapon (LRHW): Dark Eagle," Congressional Research Service, https://www.congress.gov/crs_external_products/IF/PDF/IF11991/IF11991.36.pdf

[24] Yi Feng, Shenshen Liu, Wei Tang, Yewei Gui, "Aerodynamic configuration design and optimization for hypersonic vehicles," *21st AIAA International Space Planes and Hypersonics Technologies Conference* (2017), https://doi.org/10.2514/6.2017-2173; 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

[25] Cameron L. Tracy, David Wright, "Modeling the performance of hypersonic boost-glide missiles," *Science & Global Security* 28, 3 (2020), https://doi.org/10.1080/08929882.2020.1864945

roll angle resets to 0°, so as to maximize the crossrange distance traveled and the area of the threatened footprint. Note that selecting this option will greatly increase computation time, so we recommend that users uncheck this box unless they are interested in the threatened footprint.

The second option in this section, accessed through the "add complex maneuvers" button, allows for simulation of flight paths in which the glider executes multiple turns of varying direction and/or sharpness. When the user sets the initial roll angle to a nonzero value the model simulates a single, constant turn of the glider. Using the complex maneuvers option allows the user to alter the roll angle that the glider adopts at a given flight time. Consider, for example, a trajectory in which a missile steers around a defended area located between the missile's launch site and its target.[26] First, the missile would turn in either crossrange direction, thus avoiding the defended region. However, after passing that region it would need to turn back toward the downrange direction to approach its target. In this section of the application, users can provide the instructions necessary to simulate this sort of maneuvering. Clicking the button labeled "add roll change" allows a user to input a new roll angle, as well as the time in seconds, measured from the start of glide, at which the glider should adopt that roll angle. Users can add as many of these roll angle modifications as they desire. In the simulation, the glider will instantaneously adopt each provided roll angle at the indicated time, altering the direction of the lift force it generates and redirecting its flight path accordingly.

Running the calculation

Once a user has input all necessary parameters, clicking the blue button labeled "run simulation" will prompt the application to simulate the glider's flight. In this simulation, the glider is automatically inserted into the atmosphere at its equilibrium glide altitude, where the lift it generates matches the force of gravity.

When the simulation is complete, several numbers and plots will appear at the bottom of the page. First, summary statistics provide information on key values, like the total distance of glide in the downrange and crossrange directions and the total glide time. Below that, several plots display flight altitude, velocity, time, and crossrange distance traveled, all as a function of downrange distance traveled. The plot of altitude as a function of range will generally display phugoid motion that is typical of hypersonic glide, as the vehicle bounces between more and less dense portions of the atmosphere.[27] The plot of velocity as a function of range shows how drag forces continuously reduce flight speed during glide, and the plot of flight time as a function of range illustrates the effects of this velocity reduction on payload delivery time. If a roll angle of 0° is used, the plot of crossrange distance as a function of downrange distance will show an unusual

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[26] David Wright, Cameron L. Tracy "Hypersonic weapons: Vulnerability to missile defenses and comparison to MaRVs," *Science & Global Security* 31, 3 (2023), https://doi.org/10.1080/08929882.2023.2270292

[27] N.X. Vinh, J.S. Chern, C.F. Lin, "Phugoid oscillations in optimal reentry trajectories," *Acta Astronautica* 8, 4 (1981), https://doi.org/10.1016/0094-5765(81)90001-1

sawtooth-like pattern. Careful attention to the y-axis will show that this variation in crossrange is on the order of micrometers, reflecting negligible computational artifacts. All data shown in these plots is also provided in tabular form at the bottom of the screen, and can be easily exported to a spreadsheet for further analysis.

If the user checked the "calculate threatened footprint" box, two additional plots will appear. The first, titled "footprint analysis" displays the threatened footprint, as projected onto a two-dimensional plot of downrange and crossrange distance. This plot is derived from the simulation of multiple trajectories in which the glider executes increasingly sharp turns, as described previously. Above this plot, the approximate area of the threatened footprint is provided. Below, the footprint is projected onto a map, showing the specific region of the globe threatened by this missile, assuming it were to begin maneuvering at the start of the simulation. The user can enter initial latitude and longitude coordinates, as well as a flight angle measured from the local north, to change the projection region. The blue tab indicating the glide starting point can also be dragged to the desired location on the map. After dragging the tab or editing the associated numerical values, pushing the red "project footprint" button will update the projection. Note that straight paths over Earth's surface, when projected onto a two-dimensional map, will appear curved unless following the equator or a line of longitude. The extent of this distortion increases with distance from the equator.

If the user runs a simulation using initial flight conditions associated with the start of a particular missile's glide phase, the calculated footprint will represent a vehicle that began maneuvering at the earliest possible time. However, one might instead wish to calculate the threatened footprint associated with maneuvering at a later point in time. Consider, for instance, an attack against a target nation possessing ground-based radars that, due to horizon effects, detect a glider late in its glide phase.[28] A user interested in calculating the threatened footprint at the time of radar detection of the glider can simply run their calculation using flight conditions corresponding to this time, which can be determined from a previous calculation using initial flight conditions corresponding to the start of glide.

Use cases

Our intent is to provide a tool for the analysis of realistic scenarios of hypersonic weapon use, and for quantification of the capabilities, limitations, and security implications of this class of missile technologies. Here, we describe two example use cases to illustrate possible applications of the *Hypersonic Glide Vehicle Simulator*.

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[28] James M. Acton, "Silver bullet? Asking the right questions about Conventional Prompt Global Strike," Carnegie Endowment for International Peace, (2013), https://carnegie-production-assets.s3.amazonaws.com/static/files/cpgs.pdf

The first use case deals with quantification of target ambiguity, referring to a target state's uncertainty about where a hypersonic glide weapon will strike.[29] This ambiguity, which results from the maneuverability of hypersonic weapons, could enhance the risk of inadvertent escalation in a conflict. If, for example, two states were within the threatened footprint of a glider, both might think they are under attack during the missile's flight, even if the attacker meant only to target one. Even if the threatened footprint were wholly contained within a single state's borders, that state might be unsure of whether an attack is targeting their nuclear forces, possibly provoking a nuclear response, or only their conventional forces, which may fall short of the threshold for a nuclear response. This application provides a means of quantifying this threatened area at any stage of a glide vehicle's flight.

The second example use case deals with determination of a glide vehicle's mid-course maneuverability, which may could allow hypersonic missiles to carry out missions that less maneuverable weapons, like ballistic missiles, could not. For example, maneuverability could enable an attacker to avoid overflight of certain regions, such as a state not involved in a conflict.[30]

Use case 1: quantifying target ambiguity

Consider, as an illustrative example, a missile launched from the Russian homeland toward the United States. If a missile without significant maneuvering capability were used, its destination would be clear to US analysts shortly after its launch. For a highly maneuverable weapon, the situation would be quite different. A glide missile in flight might simultaneously threaten US ICBM silo fields in Montana, North Dakota, and Wyoming (suggesting a counterforce attack); major US population centers like New York City, Washington, DC, or Los Angeles (suggesting a countervalue attack); or non-nuclear US military assets (suggesting a conventional attack).[31] Because US officials would likely respond differently in each of these attack scenarios, the maneuverability of a glide vehicle could give rise to dangerous uncertainty, misperception, and risks of inadvertent escalation. Of course, this depends sensitively on the maneuvering capabilities of this missile, which we will now quantify using the *Hypersonic Glide Vehicle Simulator*.

Russia has deployed its Avangard system, a nuclear- or conventionally-armed, intercontinental-range hypersonic glide vehicle, on its SS-19 rocket boosters.[32] The SS-19 has a quoted range of 10,000 km, which corresponds to a maximum velocity, at the end of the boost

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[29] James M. Acton, "Debating Conventional Prompt Global Strike," Carnegie Endowment for International Peace, (2013), https://carnegie-production-assets.s3.amazonaws.com/static/files/Acton-CPGS.pdf

[30] David Wright, Cameron L. Tracy "Hypersonic weapons: Vulnerability to missile defenses and comparison to MaRVs," *Science & Global Security* 31, 3 (2023), https://doi.org/10.1080/08929882.2023.2270292

[31] Kosta Tsipis, "Physics and calculus of countercity and counterforce nuclear attacks," *Science* 187, 4175 (1975), https://doi.org/10.1126/science.187.4175.393

[32] Center for Strategic and International Studies, "Avangard," https://missilethreat.csis.org/missile/avangard/; Center for Strategic and International Studies, "UR-100 (SS-19)," https://missilethreat.csis.org/missile/ss-19/

phase, of about 7 km/s (see Eq. (7)).[33] The maximum velocity this rocket actually achieves will depend on the payload mass (for example, the number of warheads) and the boost trajectory, so the 7 km/s figure we assume here is a rough approximation. Assuming the weapon loses approximately 15% of its velocity in the pull-up maneuver, we set its initial glide speed to 6 km/s. We assume the Avangard glide vehicle possesses aerodynamic characteristics similar to the HTV-2, given its similar geometry: a ballistic coefficient of 4,680 kg/m^2 and L/D of 2.6.

Running the model using these parameters, and leaving all others at their default values, provides data on glider performance and the threatened area. However, before further analysis we must project that area onto the map region of interest. We assume that the missile is launched from the Kozelsk missile field, where SS-19s are based, which is located at approximately 53.85 latitude, 35.78 longitude.[34] We further assume an initial, ballistic trajectory that appears as a counterforce attack on US ICBM silos at Minot Air Force Base in North Dakota. This target is about 8,000 km away from Kozelsk following a straight line that passes through Greenland and Manitoba. We assume the missile follows a ballistic path for half the distance to its target before reentering the atmosphere, then executes a pull-up maneuver over a 1,000 km distance. It will therefore begin its glide phase over Canada's northeastern border, around 69.76 latitude, -67.95 longitude. We use these coordinates for the map projection, and set the map flight angle to 234° which, without maneuvering, would carry the glider to Minot.

The results of this calculation show that the glider could, from the start of its glide phase, fly an additional 9 minutes, covering ~7,000 km, though to reach Minot it would need to glide only ~3,000 km. The glider could sacrifice some of its excess range capacity to execute glide phase maneuvers, turning away from its southwestern flight direction toward the northwest or southeast. Figure 4 illustrates the region it could reach were it to begin maneuvering at the start of its glide phase.

We see from this analysis that an Avangard-like glide vehicle could, under these flight conditions, threaten essentially the entire continental United States. Thus, a hypothetical counterforce strike could not be clearly distinguished from, for example, a countervalue strike against Washington, DC, or a conventional attack on a non-nuclear military installation. This would greatly complicate the decisionmaking of US officials tasked with formulating a response to such an attack prior to missile impact.

While the example described above deals with a long-range, strategic strike scenario, the *Hypersonic Glide Vehicle Simulator* is also useful for analysis of tactical or theater-scale scenarios. Consider, for example, a hypothetical conflict in the South China Sea. China has deployed its DF-17 hypersonic glide missiles to the Brigade 616 installation in Ganzhou, located at approximately

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[33] John Pike, Charles Vick, Mirko Jacubowski, Patrick Garrett "UR-100N / SS-19 Stilleto," Federation of American Scientists, https://nuke.fas.org/guide/russia/icbm/ur-100n.htm

[34] Hans Kristensen, "Russian ICBM Upgrade at Kozelsk," Federation of American Scientists, 5 September 2018, https://fas.org/publication/kozelsk-icbm-upgrade/

25.90 latitude, 114.96 longitude.[35] The DF-17 reportedly uses the same booster as the DF-16B, based on its maximum range of approximately 1,000 km and maximum velocity of about 3 km/s.[36] Given that the DF-17 is a relatively short-range weapon, we assume it is a less advanced system than the HTV-2, and therefore assume a lower *L*/*D* of 2.2, with the same ballistic coefficient. We further assume a 15% velocity loss in the pull-up phase.

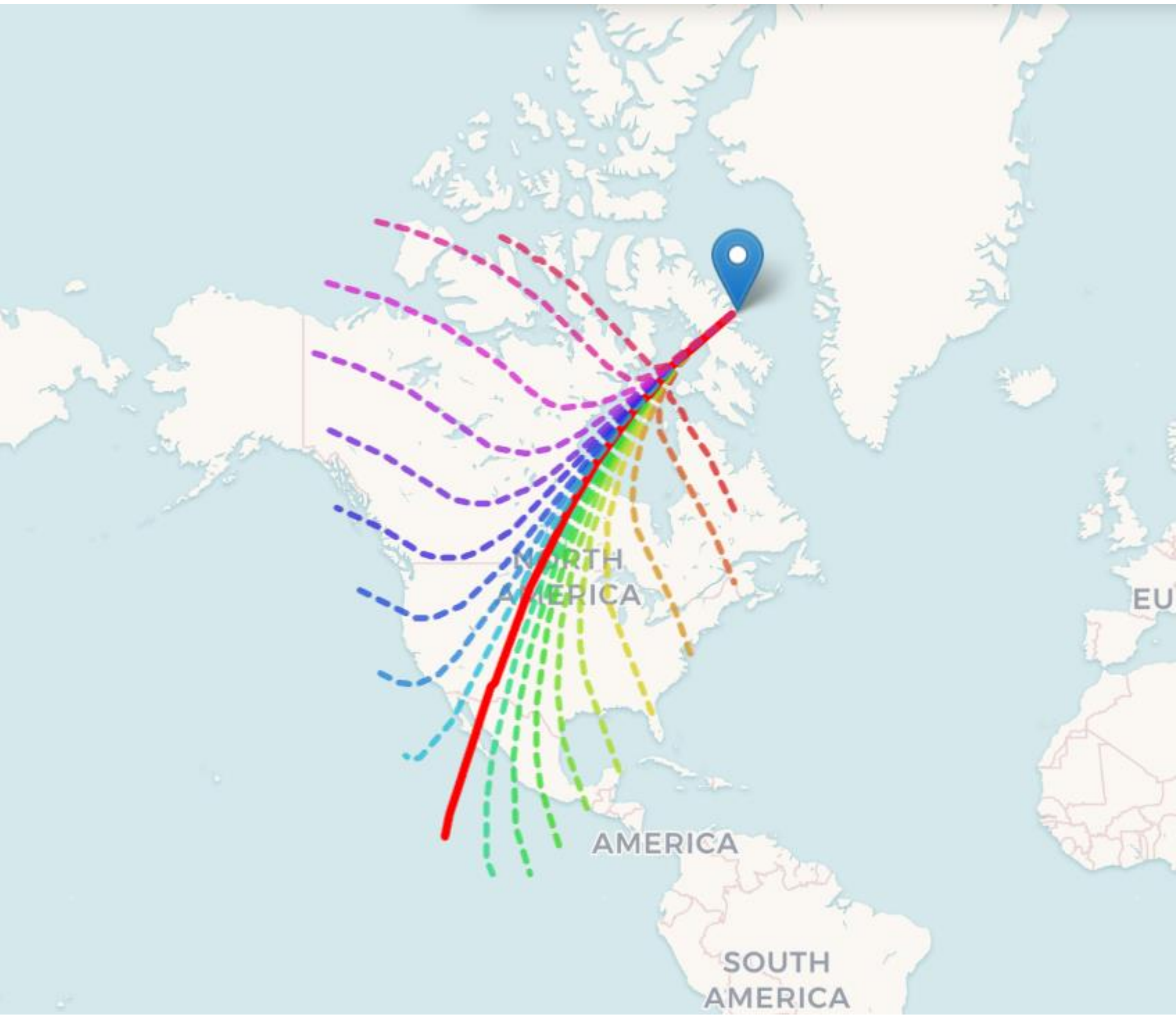

Figure 4: The threatened footprint of a notional Russian hypersonic glide missile, based on the Avangard, carrying out a counterforce strike against US ICBM silos. At the onset of its glide phase the missile threatens essentially the entirety of the continental United States.

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[35] Chris Buckley, Pablo Robles "The missiles threatening Taiwan," *The New York Times*, 29 September 2025, https://www.nytimes.com/interactive/2025/09/29/world/asia/china-missiles.html

[36] Peter Wood, Roger Cliff, "A case study of the PRC's hypersonic systems development," Department of the Air Force, China Aerospace Studies Institute (2020), https://www.airuniversity.af.edu/CASI/Display/Article/2334616/a-case-study-of-the-prcs-hypersonic-systems-development/

Using these parameters, we obtain the results shown in Figure 5. A DF-17 launched from Brigade 616 toward the center of the South China Sea, starting its glide phase near China's southern coastline, could threaten a substantial portion of this region, but would probably not threaten nearby states like Taiwan or the Philippines. Striking the latter targets would require a launch in a different direction, thus limiting target ambiguity.

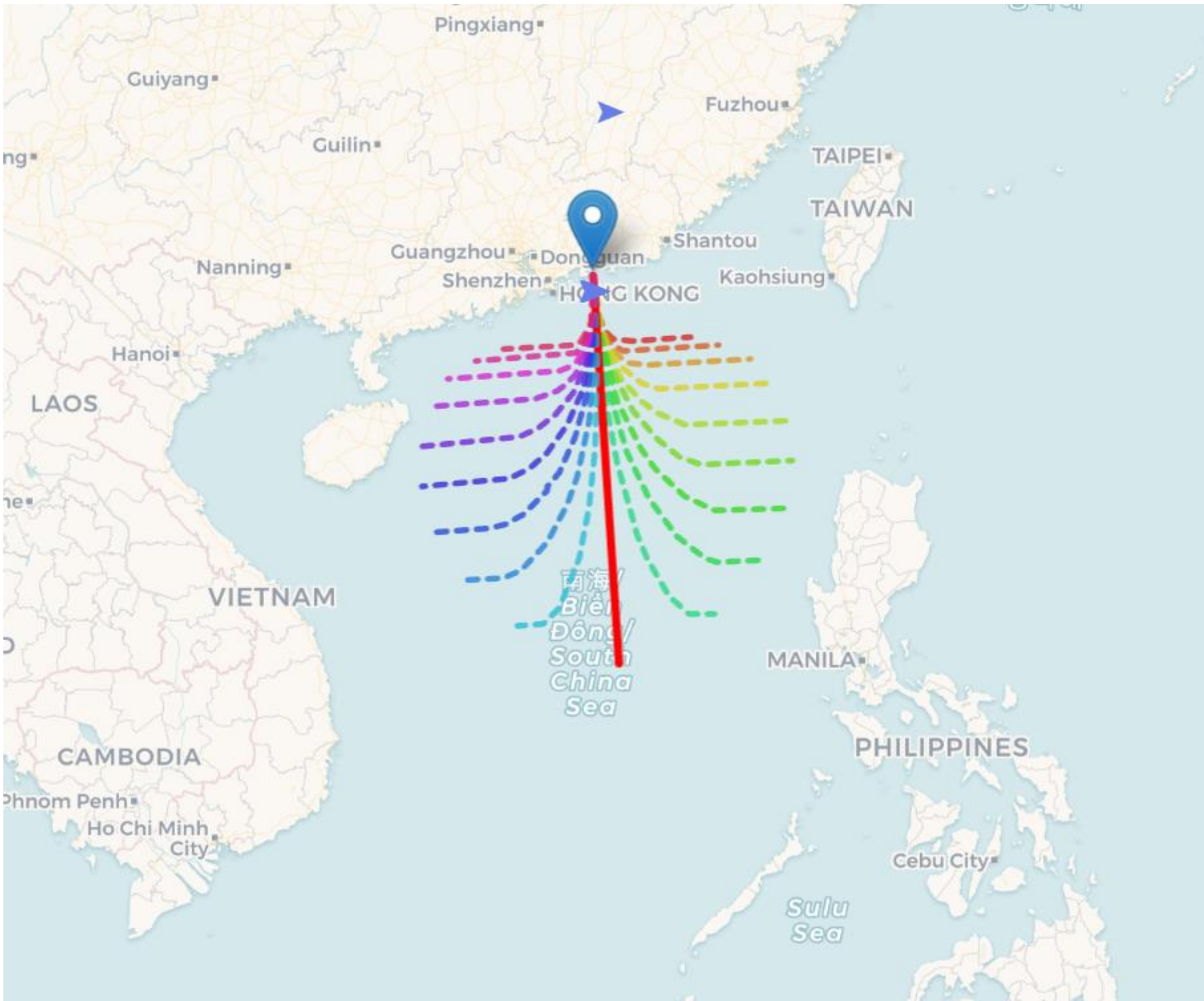

Figure 5: The threatened footprint of a notional Chinese hypersonic glide missile, based on the DF-17, carrying out an attack on a ship located near the center of the South China Sea. At the onset of its glide phase the missile threatens a large region, but does not threaten nearby states. As it flies, the missile's threatened footprint will continuously shrink.

Use case 2: quantifying overflight avoidance capabilities

Many ballistic missiles are capable of some degree of maneuvering following the boost phase if equipped with post-boost vehicles, like those used in multiple independently targetable reentry vehicle (MIRV) systems, or with maneuverable reentry vehicles (MARVs).[37] Hypersonic glide vehicles, however, offer the potential for more extensive, sustained mid-course maneuvering during glide. For many missions, large-scale maneuvering would be of little utility, as the shortest distance between a launch site and target is measured along a straight line. This capability could, however, allow an attacker to avoid overflight of certain regions, although this would mean sacrificing achievable range and flight speed, and increasing delivery time.

What regions might an attacker wish to avoid? First, they might seek to bypass defended regions. If an adversary were to deploy mid-course missile defenses in limited numbers, such that they could attempt to intercept missiles only in a particular region, then glider maneuverability could enable an attacker to avoid these defenses. Assume, for instance, that the Glide Phase Interceptor, which the United States plans to deploy in the 2030s as part of its Aegis missile defense system[38], were designed with a range of approximately 2,500 km, comparable with that of Aegis's SM-3 Block IIA interceptors currently deployed for mid-course intercept of ballistic missiles.[39] One such system could attempt intercept within a region about the size of Europe, so a highly maneuverable, long-range hypersonic missile might fly around this defended region. This may not be a realistic use case, however, since the use of missile defense systems typically involves deployment to multiple sites producing large, overlapping defended regions.[40]

An attacker might instead seek to maneuver a glider outside the range of an adversary's sensors in order to delay that adversary's awareness of an incoming strike. This could be practical for ground-based, below-the-horizon radar sensors, since the low altitude glide of hypersonic missiles yields short radar detection ranges.[41] However, a glider could not similarly bypass space-based infrared (IR) sensors of the sort that the United States, Russia, and China deploy, since these sensors images large portions of Earth and are sensitive to the IR light emitted by hypersonic glider vehicles.[42]

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[37] Steven T. Dunham, Robert S. Wilson, "The missile threat: A taxonomy for moving beyond ballistic," Aerospace Corporation (2020), https://csps.aerospace.org/sites/default/files/2021-08/Wilson-Dunham_MissileThreat_20200826_0.pdf

[38] Jen Judson, "Congress demands quicker fielding of hypersonic weapons interceptor," *DefenseNews*, 18 December 2023, https://www.defensenews.com/pentagon/2023/12/18/congress-demands-quicker-fielding-of-hypersonic-weapons-interceptor/

[39] Center for Strategic and International Studies, "Standard Missile-3 (SM-3)," https://missilethreat.csis.org/defsys/sm-3/

[40] George Lewis, "Aegis Ashore vs THAAD," *mostlymissiledefense*, 27 July 2015, https://mostlymissiledefense.com/2015/07/27/aegis-ashore-vs-thaad-july-27-2015/

[41] James M. Acton, "Silver bullet? Asking the right questions about Conventional Prompt Global Strike," Carnegie Endowment for International Peace, (2013), https://carnegie-production-assets.s3.amazonaws.com/static/files/cpgs.pdf

[42] Cameron L. Tracy, David Wright, "Modeling the performance of hypersonic boost-glide missiles," *Science & Global Security* 28, 3 (2020), https://doi.org/10.1080/08929882.2020.1864945; Graham V. Candler, Ivett A. Leyva, "Computational fluid dynamics analysis of the infrared emission from a generic hypersonic glide vehicle," *Science & Global Security* 30, 3 (2022), https://doi.org/10.1080/08929882.2022.2145777

A more realistic application of glide phase maneuvering would be avoidance of overflight of a state not involved in a conflict.[43] This capability is most relevant for long-range, strategic missions in which a missile would traverse a large portion of the globe. In a hypothetical nuclear exchange between the United States and China, for example, both might be interested in the use of glide vehicles to avoid overflight of Russia, which sits directly between the two. Were the United States to launch an ICBM toward China, for instance, Russia might misperceive this as a nuclear attack on its territory, and respond accordingly.

Would the use of a hypersonic glide vehicle allow the United States to attack China without overflying Russia? Using the *Hypersonic Glide Vehicle Simulator*, we can address this question quantitatively. We first assume the use of a high L/D glider like the HTV-2, launched on a powerful ICBM booster. According to public statements, the United States currently has no plans to deploy an intercontinental-range hypersonic glide weapon, focusing instead on theater-range systems. However, it has dedicated a substantial amount of funding and effort to the testing of such a weapon. The United States flight tested the HTV-2 twice, and in 2020 the US Air Force accidentally released a call for industry proposals to work on a hypersonic glide vehicle for use with the upcoming Sentinel ICBM.[44]

Were the United States to launch this hypothetical weapon at China, it could attempt to avoid overflight of Russia using a trajectory that initially travels over the northern Pacific Ocean. Reentering ~1,000 km west of Japan's eastern coastline, the glide vehicle might then turn west to approach China's eastern coastline. For the purposes of this analysis we assume a counterforce strike launched from Malmstrom Air Force Base in Montana, targeting Brigade 616 in Ganzhou, the military installation from the previous example use case.

We use vehicle parameters for the HTV-2 (ballistic coefficient of 4,680 kg/m^2 and L/D of 2.6), and assume an initial glide speed of 6.1 km/s. This speed is identical to that seen in flight testing of the HTV-2 launched on a Minotaur-IV booster, which is a repurposed Peacekeeper ICBM.[45] Since we are interested here in specific maneuvers of the glide vehicle rather than the threatened footprint, we uncheck the "calculate threatened footprint" box in the application to speed up the simulation. We want the vehicle to turn sharply to its right from the start of glide, so we enter an initial roll angle of 60°. This will reorient the vehicle's lift force toward China, causing the vehicle to turn as it flies (and causing it to fly at lower altitudes through denser air, since less of the lift force acts counter to Earth's gravitational force).

Once the vehicle has turned sufficiently that it is heading directly toward its target, it should change its roll angle to prevent further turning. Thus, we use the "add complex maneuvers" option

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[43] National Research Council, *U.S. Conventional Prompt Global Strike: Issues for 2008 and Beyond* (Washington, DC: National Academies Press, 2008), https://doi.org/10.17226/12061

[44] Steve Trimble, "USAF errantly reveals research on ICBM-range hypersonic glide vehicle," *Aviation Week*, 18 August 2020, https://aviationweek.com/defense/missile-defense-weapons/usaf-errantly-reveals-research-icbm-range-hypersonic-glide-vehicle

[45] James M. Acton, "Hypersonic boost-glide weapons," *Science & Global Security* 23, 3 (2015), https://doi.org/10.1080/08929882.2015.1087242

to change the roll angle to 0° after 600 seconds of glide. Note that these optimal roll angles and timings were determined through an iterative process; users should adopt a similar trial-and-error approach.

Running the simulation outputs a glide trajectory that veers sharply to the right for the initial portion of flight, then continues straight after 600 seconds of glide. Because we are interested in simulating an attack from Malmstrom Air Force Base on Brigade 616, we need to change the initial coordinates and flight direction on the resulting map projection. A straight line from Malmstrom toward a point approximately 1,000 km off the coast from Tokyo will pass through 32.25 latitude, 150.00 longitude. We set these as the starting coordinates for glide. This point is ~8,500 km from Malmstrom Air Force Base, well within the range of modern ICBMs. We further set the initial flight direction to 223°, which is oriented along a straight line passing through this point from Malmstrom Air Force Base, since the ballistic phase prior to glide proceeds along a straight flight path. Figure 6 displays the resulting map projection.

Figure 6: The glide trajectory of a notional US hypersonic glide missile, based on the HTV-2 and starting glide at a velocity of 6.1 km/s, carrying out an attack on a Chinese missile installation in Ganzhou while avoiding overflight of Russia.

From this analysis we see that a notional, highly capable glider could execute this maneuver and retain enough velocity to reach its target in Ganzhou. However, this is near the maximum achievable range when executing such a maneuver. The plot of velocity as a function of range shows that, by the time this glider reached its target, drag would have significantly slowed its flight to approximately 2 km/s (about Mach 6), which is at the lower end of the hypersonic regime. At this flight speed the missile would likely be vulnerable to interception by terminal phase missile defenses.[46] This result further indicates that a less capable design, such as one with slightly lower L/D, would be unable to fly this trajectory. This is illustrated by running the same simulation with an L/D value of 2.2, characteristic of systems like the C-HGB, which the United States currently deploys on its Long-Range Hypersonic Weapon. Adopting this value and changing the timing of the roll angle change to 540 seconds to account for a slightly wider turn radius, we find that such a system would fail to reach its target in Ganzhou, as shown in Figure 7.

Figure 7: The glide trajectory of a notional US hypersonic glide missile, with a lift-to-drag ratio slightly below that of the HTV-2 ($L/D = 2.2$) and an initial glide velocity of 6.1 km/s, attempting an attack on a Chinese missile installation in Ganzhou while avoiding overflight of Russia. This missile lacks the range necessary to reach its target when executing this maneuver.

This analysis demonstrates the strong dependence of the capabilities of hypersonic glide systems on their specific technical parameters. It further shows the utility of computational

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[46] David Wright, Cameron L. Tracy "Hypersonic weapons: Vulnerability to missile defenses and comparison to MaRVs," *Science & Global Security* 31, 3 (2023), https://doi.org/10.1080/08929882.2023.2270292

modeling for investigation of the specific missions that hypersonic glide vehicles can and cannot carry out. As in the previous use case, the methods described here are equally applicable to the analysis of tactical, theater-range strikes.

Conclusions

The *Hypersonic Glide Vehicle Simulator* provides an easy-to-use means of performing approximate analysis of the capabilities and military utility of hypersonic glide weapons. To date, most assessments of the security implications of these systems lack any consideration of their quantitative capabilities or the technical basis for their performance. The use cases presented above, however, show that both the capabilities and the security implications of hypersonic weapon systems are closely tied to the specific technical parameters of particular missile designs. Using the *Hypersonic Glide Vehicle Simulator*, future analyses can more easily account for the influence of those factors.

This tool also facilitates mission-based analysis, in which hypersonic weapon performance is considered not in the abstract, but in terms of a specific, realistic military role. While mission-based analysis is rarely found in the international security literature, it is necessary to inform decisions about weapons development, acquisition, and use. See, for example, recent work by the Congressional Budget Office using computational tools derived from the same flight models that the *Hypersonic Glide Vehicle Simulator* is based on.[47] They simulate the use of hypersonic weapons in two notional military scenarios: conflict between the United States and Russia in the Baltics and conflict between the United States and China in the South China Sea. Through mission-based analysis they find that, contrary to common claims of a nascent hypersonic revolution, these weapons would perform no better in these missions than would much cheaper ballistic missile technologies. Through use of the *Hypersonic Glide Vehicle Simulator*, others working on these issues can now easily replicate and extend this form of analysis.

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[47] Corinne Kramer, David Mosher, Edward G. Keating, "U.S. hypersonic weapons and alternatives," Congressional Budget Office (2023), https://www.cbo.gov/system/files/2023-01/58255-hypersonic.pdf