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REPLY

"Computational Fluid Dynamics Analysis of the Infrared Emission from a Generic Hypersonic Glide Vehicle"—A Response

Cameron L. Tracy [a] and David Wright [b]

[a]Center for International Security and Cooperation (CISAC), Freeman Spogli Institute for International Studies, Stanford University, Stanford, California, USA; [b]Visiting Scholar, Laboratory for Nuclear Security and Policy, Department of Nuclear Science and Engineering, Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, USA

ABSTRACT

A recent paper by Candler and Leyva in *Science & Global Security* comments on our 2020 paper "Modelling the Performance of Hypersonic Boost-Glide Missiles" analyzing the capabilities of hypersonic boost-glide weapons. They provide useful new data on several previously uncertain aspects of glide vehicle aerodynamics and report results from computational fluid dynamics calculations of heating and infrared light emission from hypersonic vehicles during the glide phase. They report infrared emissions lower than those we reported but still above the minimum detection threshold of modern U.S. space sensors. We discuss how Candler and Leyva's new data can be incorporated into our analytical model and identify significant, unresolved discrepancies between their results and those of a previously published computational fluid dynamics analysis of the same glide vehicle. Finally, we comment on the role of social processes in the construction of knowledge about hypersonic weapon performance.

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Introduction

Our 2020 article in this journal, "Modelling the Performance of Hypersonic Boost-Glide Missiles," reported a computational study of the flight performance of a representative hypersonic glide vehicle based on the U.S. Hypersonic Technology Vehicle 2 (HTV-2).[1] Given widespread claims of a coming hypersonic revolution and of the purported superiority of hypersonic missiles to more common ballistic missile designs, we quantitatively compared the flight performance of these two missile technologies. We were surprised to find dramatic deviations between typical claims of hypersonic missile performance and the predictions of our analytical model.

CONTACT Cameron L. Tracy cltracy@stanford.edu Center for International Security and Cooperation (CISAC), Freeman Spogli Institute for International Studies, Stanford University, Stanford, CA, USA.

We found that (1) hypersonic glide vehicles would reach their targets no faster than ballistic missiles launched on depressed trajectories using the same booster, (2) hypersonic glide vehicles would exhibit slower flight speeds than these ballistic missiles for much of their flight, and (3) hypersonic glide vehicles would be visible to currently deployed space-based sensors during their glide phase. We attributed the divergence between common claims of hypersonic missile performance and our findings to the influence of heterogeneous engineering, a process well-characterized in the science and technology studies literature wherein proponents of a particular technology socially construct technical "facts" that are conducive to the success of that technology.[2]

In publishing our findings and the details of our analytical model, we hoped that others would build on our results to further determine the capabilities and international security implications of hypersonic weapons. We welcome Candler and Leyva's contribution to this effort with their current article.[3]

In their work, Candler and Leyva use computational fluid dynamics (CFD) calculations to address one aspect of our findings: the visibility of a representative glide vehicle to currently deployed space-based sensors. They provide useful new data on several previously uncertain aspects of glide vehicle aerodynamics. These represent a significant improvement to the assumptions noted in our 2020 article, for which we used values of the lift-to-drag ratio (L/D) and ballistic coefficient (β) estimated previously by Acton,[4] and for which we lacked high-quality data on the angle of attack (α) typical of HTV-2 flight and on the boundary layer transition.

Incorporating these new data in their CFD calculations, Candler and Leyva confirm a central conclusion of our 2020 article: Currently deployed space-based sensors should be capable of observing a hypersonic glider in flight throughout most of the hypersonic velocity regime. While reporting infrared (IR) light emissions lower than those we reported, they nonetheless find emissions several times greater than the detection threshold of modern U.S. sensors and write that the representative glider would be "detectable by … sensors from the Space-Based Infrared System [SBIRS]" for sufficiently high vehicle speeds.[5]

To further our common goal of elucidating the precise capabilities and security implications of hypersonic weapons, we discuss several issues below. We first discuss how the new data provided by Candler and Leyva can be incorporated into our analytical model, improving agreement between our calculations and theirs. We then discuss Candler and Leyva's results in light of a previously published CFD analysis of the same system.[6] Finally, we address Candler and Leyva's interpretation of their findings and explain how this illustrates the role of social processes in the construction of knowledge about hypersonic weapon performance.

Compatibility with our analytical model

As noted above, Candler and Leyva provide useful data on several aspects of hypersonic glide vehicle aerodynamics, which were not available when we wrote our original paper. In particular, they report an estimate of the optimal α for glide of the HTV-2 (14 degrees) and new data on the glider's L/D as a function of α. They also provide a new value of β and an improved description of the boundary layer transition between laminar and turbulent flow over the upper surface of the glider. These new data can be incorporated into our model, allowing for direct comparison to the CFD results of Candler and Leyva, as well as those previously reported by Niu et al.

When performing our original calculations, we calculated the dynamics of the glide vehicle using Acton's parameters[7] for the HTV-2 test ($L/D = 2.6$, $\beta = 13{,}000\,\text{kg/m}^2$) and calculated the heating with Tauber's empirical equations.[8] The angles we used in the heating equation were those of the vehicle's upper surface in the approximate geometry of the vehicle reported by Niu et al., which were 11.3° and 7.6° for different parts of the body (see Candler and Leyva's Figure 5).[9] This orientation of the vehicle corresponds to $\alpha = 0$ in Candler and Leyva's coordinate system.

Since our emission estimates for $\alpha = 0$ were well above the detection threshold for SBIRS, we concluded from this that even for non-zero α the IR emission level would be high enough at the speeds we considered for SBIRS to detect the glider, which was our primary interest. We return to this issue below.

Laminar vs turbulent boundary layer flow

Candler and Leyva argue that, based on their calculations, the boundary layer flow over the upper surface of the glider should be entirely laminar, rather than turbulent as we assumed. They note that more work is needed on this issue, which would be useful since the boundary layer transition is a complicated phenomenon that depends on a number of factors.[10]

Assuming the boundary layer is laminar, we can incorporate that assumption into our model by using Tauber's equation for heat transfer in the laminar case, which takes the form:[11]

$$\frac{dq}{dt} = 2.53 \times 10^{-5}\left(\frac{(\cos\theta)^{0.5}\sin\theta}{x^{0.5}}\right)\left(1 - \frac{h_w}{h_0}\right)\rho^{0.5}v^{3.2}, \tag{1}$$

where dq/dt is the heat flux in J/m^{2}s, θ is the angle between the vehicle surface and the freestream flow, x is the distance along the vehicle surface in meters, h_w is the wall enthalpy, h_0 is the stagnation enthalpy, ρ is the atmospheric density in kg/m^3, and v is the vehicle velocity in m/s.

While the Tauber equations cannot be used for large values of α, we can compare results of the models for $\alpha = 0$. Running our model with the laminar equation and comparing to Candler and Leyva's result for the same conditions (laminar flow, altitude = 49.7 km, $v = 6$ km/s, $\alpha = 0$) gives a result for IR emission in the short-wavelength IR (SWIR) band of 91 kW/sr, which is within 30% of Candler and Leyva's value of about 120 kW/sr given in their Figure 4, suggesting that for small values of α the two models are in reasonable agreement.

Value of the ballistic coefficient

In our 2020 paper we assumed a value of β reported by Acton in his analysis of the HTV-2 test flight.[12] The dynamics of the vehicle during glide (velocity profile, range, and flight time) depend weakly on β for a given initial glide speed v since changing β will change the drag at a given altitude but will also change the glide altitude in such a way that the vehicle feels essentially the same drag force.[13] This implies that Acton's fitting to HTV-2 flight test data[14] constrained the value of L/D much more tightly than it did the value of β. It also implies that using a different value of β has little effect on the analysis in our original paper of the dynamics of hypersonic vehicle flight.

Heating of the vehicle, however, does depend strongly on both L/D and β. Using the value of β that Candler and Leyva report (4,680 kg/m^2) rather than Acton's value (13,000 kg/m^2) decreases the predicted IR radiance in the SWIR band using either Tauber's laminar or turbulent equation for heat transfer by about a factor of two for $v = 6$ km/s. This difference does not matter much for speeds well above Mach 5 since the predicted IR radiance is significantly above the estimated SBIRS detection limit. It could matter at speeds closer to Mach 5, depending on the actual detection limits of SBIRS. However, an attacker could not have confidence that its glider would not be detected.

Comparison with prior CFD results

While Candler and Leyva compare their CFD results with those reported in our 2020 article, they do not address previously published CFD calculations of IR light emission from the same representative hypersonic glide vehicle. In their 2019 article, Niu et al. report a study of IR emission from the same representative glide vehicle that Candler and Leyva analyze, using CFD techniques similar to theirs.[15] They address many of the same issues, including the effects of α on IR emission. However, Niu et al. find significantly higher emission in the SWIR band than Candler and Leyva.[16]

Understanding the origin of the difference in these results is clearly important for forming conclusions about the detectability of these weapons. Candler and Leyva and Niu et al. appear to disagree by a significant factor in their calculated values of the IR emission in the SWIR band from the upper surface of the vehicle at $\alpha = 14^{\circ}$. In particular, for $v = 5.4\,\text{km/s}$, $\alpha = 14^{\circ}$, and $\beta = 4{,}680\,\text{kg/m}^2$, which corresponds to a glide altitude of about 55.5 km, Candler and Leyva report radiance of about 18 kW/sr (see their Figure 8). Niu et al. find a value of about 100 kW/sr for similar conditions ($V = 5.4\,\text{km/s}$, $\alpha = \sim 15^{\circ}$, and altitude $= 50\,\text{km}$), which can be estimated from their Figure 16b. The difference in atmospheric densities at these two altitudes explains some of this difference but does not appear to explain all of it.

Moreover, these discrepancies cannot be attributed solely to differences in the treatment of turbulence in the boundary layer, as Candler and Leyva's calculations find that the centerline temperatures on the upper surface of the vehicle at the condition of maximum *L/D* are essentially independent of whether the flow is laminar or turbulent.

A similarly large discrepancy between Candler and Leyva's results and those reported by Niu et al. is found in their analysis of the effects of α on IR emission. Niu et al. find that increasing α from 0° to 10° reduces the radiant intensity of the glider's upper surface by roughly a factor of two, and that a further increase in α to 20° slightly *increases* this intensity. In contrast, Candler and Leyva instead find a factor of three reduction in IR emissions from the upper surface when the vehicle rotates from $\alpha = 0^{\circ}$ to 10° and by another factor of two reduction as α goes from 10° to 20° (see their Figure 4).

The origins of these discrepancies remain unclear, as does the question of which CDF calculation may better represent the physical situation.

Implications for the detection of hypersonic weapons

In their conclusion, Candler and Leyva write: "Tracy and Wright claim that there are social origins ('heterogeneous engineering') to the purported misperceptions about the capabilities of hypersonic weapons, including the perceived difficulty of detecting them during flight. However, the present analysis shows that this claim is not correct." In other words, they state that their analysis shows that there are no social origins to the commonly stated misperception that hypersonic weapons are difficult to detect in flight.

However, in their analysis Candler and Leyva confirm our conclusion that currently deployed space-based sensors can observe hypersonic gliders during flight at high speeds relevant to the HTV-2. While their analysis suggests this observability may occur at somewhat higher glide speeds than we estimated in our original paper, their analysis confirms that common claims about glider observability are misperceptions, and that rigorous technical analysis makes clear the erroneous nature of these misperceptions.

But if those misperceptions lack a technical basis, as both our analysis and Candler and Leyva's analysis shows, then their origins must be due to other factors. Candler and Leyva do not suggest what those factors might be other than social factors.

As a result, Candler and Leyva's assertion that there are no social origins of beliefs regarding the detectability of hypersonic weapons in fact provides an illustration of heterogeneous engineering in action. Consider the findings that might have resulted from their calculations. Broadly speaking, two outcomes were possible: Their model could have predicted glider IR light emission either below the detection threshold of currently deployed sensors, or equal to or greater than that threshold. Had they calculated emission below the threshold, Candler and Leyva could correctly have interpreted this as a refutation of our findings. In their current article they interpret the inverse—emission greater than the SBIRS detection threshold—in precisely the same manner, as a refutation of our analysis. Regardless of their computational results, only a single outcome was possible: the social construction of technical "facts" favoring the technology in question.

Conclusions

Understanding of the capabilities of hypersonic weapons remains poor among publics, analysts, government officials, and even technical communities. This is due, in large part, to a lack of open-source technical assessment of hypersonic missile performance. Despite recent work on this topic, there remains a pressing need for further analysis to support technically informed decisions about weapons development, procurement, and use.

Candler and Leyva's article is an important contribution to this ongoing effort. However, their paper also highlights persistent uncertainties, illustrated by the unexplained disagreement between their results and those of Niu et al., as well as questions of the proper interpretation of their results.

ORCID

Cameron L. Tracy http://orcid.org/0000-0002-0679-8522

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12. Acton, "Hypersonic Boost-Glide Weapons."
13. The value of β affects the glide altitude h, which enters the drag equation in the form $R_e + h$, where R_e is the radius of the Earth. A change in h by 10 km changes the drag force by less than a percent.
14. Acton, "Hypersonic Boost-Glide Weapons."
15. Niu et al. "Infrared Radiation."
16. Niu et al.'s results agree well with those reported in our 2020 article in the case of $\alpha = 0$. Using Tauber's equation for a turbulent boundary layer as in our 2020 paper, the value we calculate for the IR emission in the SWIR band agrees within about 5% with the results that Niu et al. calculated using CFD methods (205 vs. 195 kW/sr) and under the same conditions (altitude = 50 km, $v = 5.4$ km/s, $\alpha = 0$).