Hypersonic Missile Threat Modeling, Simulation, and Assessment

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ABSTRACT

Advanced simulation techniques are needed to develop hypersonic missile threat assessments, as a cost-effective alternative, especially in a typical case of incomplete information. Current notional defense against hypersonic missiles lies somewhere between exoatmospheric ballistic missile defense and subsonic or supersonic cruise missile defense. Hypersonic glide and hypersonic cruise missiles have trajectories that lie within the atmosphere, and they travel at hypersonic speed–meaning a Mach number greater than five. These partial overlapping threat assessment approaches require a novel synthesis of methods. To aid in this threat assessment, a digital twin missile model is built to simulate and parametrically estimate performance subject to uncertainties. This model can provide valuable insight through quick and inexpensive simulation. This paper presents how the digital twin model is built for simulation based on first-order, physics-based engineering equations of aerodynamics and propulsion, where threat assessment is measured in the form of range capability and other performance measures (e.g., kinetic impacts). The model is verified by checking each equation with example calculations and validated with three baseline missiles: a rocket-powered air-to-air missile, a ramjet-powered advanced strategic air-launched missile, and a turbojet-powered antiship missile. Next, an application of hypersonic missile threat assessment based on publicly available or interpretable information of the Russian Zircon hypersonic cruise missile is presented. Finally, the sensitivity of the unknowns (lift-to-drag ratio, specific impulse, fuel type, fuel weight, etc.) and how they impact confidence in range performance capability is demonstrated. Therefore, if intelligence assets are limited or available information is conflicting, cost-effective and insightful risk-based decisions are still enabled.

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Dr. Randal Allen is the Chief Scientist and Director of Advanced Research and Development for Lone Star Aerospace. He is responsible for the growth of the intellectual property portfolio, including over sixty patents and trademarks. Current research includes stochastic optimization and explainable AI machine teaching/learning architectures for unsupervised, supervised, reinforcement learning, and natural language processing. He also has in-depth experience with rockets, satellites, and missile systems. Within aerospace, his areas of expertise are 3DOF/6DOF modeling and simulation (M&S); guidance, navigation, and control (GNC); embedded systems hardware/software integration; and hypersonic weapon systems. He is a Certified Modeling and Simulation Professional (CMSP) with the National Training and Simulation Association. He has served on subcommittees and authored publications and presentations for I/ITSEC. He is co-author of the textbook, “Simulation of Dynamic Systems with MATLAB and Simulink.” He received an A.S. from Harper College, a B.S. in Engineering Physics and an M.S. in Applied Mathematics from the University of Illinois (Urbana-Champaign), an Engineer’s Degree in Aeronautical and Astronautical Engineering from Stanford University, and a Ph.D. in Mechanical Engineering from the University of Central Florida (UCF).

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INTRODUCTION

U.S. hypersonics began in 1947 when the National Advisory Committee for Aeronautics (NASA's predecessor) established a hypersonic wind tunnel at Langley, Virginia. Since then, numerous experimental programs have researched propulsion, materials, and structures leading to more recent testing programs such as the X-43 supersonic ramjet (scramjet) attaining Mach 9.6 in 2001. These programs are typically organized into two classes: hypersonic glide vehicles (HGV) and hypersonic cruise vehicles (HCV). HGVs typically operate with rocket propulsion and glide, whereas HCVs operate with airbreathing propulsion and cruise. Both vehicles maneuver using aerodynamic surfaces, and this maneuverability is crucial, unlike ballistic vehicles. Ballistic vehicles, such as Intercontinental Ballistic Missiles, are launched with rocket propulsion and lack maneuverability. Therefore, their trajectories may be determined early in flight, making them relatively easy to intercept. Even without interception, these ballistic trajectories result in a small impact area. However, HGVs and HCVs can maneuver with glide and cruise capabilities, and they do not have to be lofted high into the atmosphere. This makes determining their trajectories extremely difficult. Factor in their hypersonic speed and one realizes there is little time for decision-making when it comes to threat neutralization.

Table 1 (Norris 2022) shows a history of various experimental hypersonic glide and cruise (airbreathing) vehicle programs and their outcomes over the past half century. Prior to 1980, there were many hypersonic *reentry vehicle* tests, which led to the success of the Space Shuttle program beginning in 1981.

Table 1 –Hypersonic Program History

Year	Description	Outcome
1978	Advanced Manned Spaceflight Capability	Not flown, canceled in 1986
1979	Advanced Maneuverable Reentry Vehicle	Flown
1982	DARPA Copper Canyon	Not flown, canceled in 1990s
1896	X-30 National Aerospace Plane	Not flown, canceled in 1990s
1995	NASA's X-34	Not flown, canceled in 2001
1996	NASA's X-33	Not flown, canceled in 2001
2001	Scramjet X-34	Mach 7 and Mach 9.6 in 2004
2002	HyFly (dual combustion ramjet)	Final attempt failed in 2010
2010	X-37B (based on X-37A)	First orbital mission
2010	X-51A (wave rider)	Mach 5.1 and 210 sec flight
2010	Hypersonic Test Vehicle 2	Unsuccessful flight

However, by examining the "outcomes" column, it is apparent that technical challenges, flight test failures, and cancelations resulted in repeated short term hypersonic programs. The associated knowledge loss and talent atrophy needs to be re-established when a new program starts.

In the present day, the U.S. has persevered with hypersonics research and development. Table 2 (Sayler 2023) shows the known unclassified government hypersonic prototype weapon programs currently funded by the DOD.

Table 2 – Current Hypersonic Prototype Programs

Agency	Program	Status
DARPA	Hypersonic Airbreathing Weapon Concept (HAWC)	Ground testing FY23
DARPA	Tactical Boost Glide (TBG)	Third test flight FY23
USA	Long Range Hypersonic Weapon (LRHW)	Prototype deployment FY23
USAF	Air-launched Rapid Response Weapon (ARRW)	Canceled, March 2023*
USAF	Hypersonic Attack Cruise Missile (HACM)	Test/development FY27
USN	Conventional Prompt Strike (CPS)	Deployment FY25

Since the DOD has not established any programs of record for hypersonic weapon acquisition, contributing to the U.S. losing its hypersonics lead to China and Russia, all the programs in the table are prototypes. It remains to be seen which will emerge as the most cost-effective solution. It appears that these weapons will be conventionally armed, which requires a precision strike.

To counter the United States' effective ballistic missile defense systems, China and Russia have developed hypersonic threats. Due to their nuclear capability, precision is not required, hence their rapid development. China fielded the DF-ZF HGV in 2020 and is currently in the process of developing a "wave rider" called Starry Sky-2 (Sayler 2023) that will be operational by 2025. Meanwhile, Russia has an HGV (Avangard) boosted by an ICBM, a ship-launched HCV (Tsirkon/Zircon), and an air-launched ballistic missile (Kinzhal/Daggar) that has been used in Ukraine. As mentioned previously, because these are hypersonic threats, there is little time for decision-making in a scenario where these are deployed. With the inconsistency of U.S. development programs, there may be limited human resources with topical knowledge. As such, can we assess hypersonic threats with limited knowledge in a timely manner?

The remainder of this paper introduces hypersonic threat modeling, simulation, and assessment, which can be used to gain valuable insight quickly and inexpensively. In subsequent sections, the paper specifically discusses modeling, verification and validation, and simulation. Simulation of the model is then applied to demonstrate how decision-makers may aggregate threat assessment and how uncertainty may impact confidence in performance capability. Therefore, if intelligence assets are limited or available information is conflicting, cost-effective, and insightful risk-based decisions are possible.

MODELING

To simulate and assess threats, a digital twin model of generic hypersonic glide/cruise vehicles is needed. One of the earliest researchers is Fleeman (2001, 2012) who presents a comprehensive approach to first-order conceptual missile design and system engineering. A first-order approach is more than sufficient to gain the necessary insight. In the text, Fleeman guides the student through the design process, introducing the necessary physics-based engineering equations describing aerodynamics, propulsion, mass properties, structures, aerothermal heating, and flight performance metrics among other measures of merit. Accompanying the text, Fleeman provides an Excel spreadsheet (Spears et al. 2022) to perform calculations associated with the *design* process. Fleeman's text is excellent, and the spreadsheet is more than adequate. However, to facilitate reverse engineering for threat analysis, it is beneficial to have the physics-based engineering equations available on a platform with optimization capability. This platform and the benefit of optimization for reverse engineering will be described next.

During a webinar on the challenges of hypersonic flight, Bowcutt (2022) discusses the need for multidisciplinary design optimization due to the increased design/performance uncertainties associated with hypersonic flight. This is yet another motivation to build the model on a platform capable of optimization, and to accommodate uncertainty with stochastic input variables. This platform and related papers have been presented to I/ITSEC over recent years (Allen 2019, 2020, 2021).

When assessing missile threats, one often wants to know the range of the threat for countermeasure purposes. If the threat is ballistic, modified projectile motion equations may be applied for range analyses. However, since our interest is hypersonic glide/cruise missiles, different equations are required. For glide vehicles, range is simply a function of altitude and the lift-to-drag ratio, which is based on the aerodynamics of the vehicle. For cruise vehicles, range is more complicated due to propulsion, but the Breguet range equation will provide the answer, given by

$$R = V_{AVG} I_{SP} \left(\frac{L}{D}\right) \ln \left(\frac{W_{BC}}{W_{BC} - W_P}\right) \qquad \text{(Equation 1)}$$

where R is range, V_{AVG} is average velocity, I_{SP} is specific impulse, L/D is the lift-to-drag ratio, W_{BC} is the weight of the vehicle before cruise, and W_P is the weight of the propellant (Fleeman, 2012, p.127). The weight of the vehicle before cruise and the weight of the propellant can be in any units, provided they are consistent such that the ratio of the natural log argument is dimensionless. Typically, units of pounds are used for weight. The lift-to-drag ratio is based on the aerodynamics of the vehicle. It too is dimensionless because lift and drag are given in consistent units. Specific impulse is a measure of propulsion efficiency, measured in units of seconds. The higher the specific impulse, the more efficient the propulsion system is at generating thrust. Finally, the average velocity may be in any unit of velocity provided that the denominator is in seconds to cancel with specific impulse (thus providing range in units of its numerator). For example, if the average velocity is measured in feet per second, then range will be measured in feet. In summary, the Breguet range equation is a measure of the vehicle's velocity, propulsion efficiency, aerodynamic efficiency, and weight characteristics. These are the four areas that need to be accounted for when performing threat analysis in terms of range capability. However, the analyst is not given these four parameters to be used in the Breguet range equation. Instead, there are other physics-based engineering equations that lead to these parameters—for example, lift-to-drag ratio. Similarly, a measure of aerodynamic efficiency may be estimated by examining flight conditions such as Mach number, altitude, and an aerodynamic parameter called angle-of-attack. This will be discussed further in the SIMULATION section below.

VERIFICATION & VALIDATION

Before a model is used for simulation, it must be verified and validated. Verification is the process of ensuring that the *model is built correctly*; while validation is the process of ensuring that the *correct model is built*. For example, a model may be developed to compute Newton's second law, which states that the sum of the external forces on an object is proportional to the rate of change of its momentum. This equation can be verified through several tests to make sure it is implemented correctly. If so, the model is considered verified, that is, it is *built correctly*. When it is time for validation, the model is presented to stakeholders to make sure it meets requirements. At this time, if it is discovered the model is intended to be used for special relativity (where Newton's second law is invalid) and the model should have implemented Einstein's equation ($E=mc^2$) instead, then the *incorrect model has been built* and is thus invalid (maybe the modeler should have paid closer attention to the requirements.) With this understanding, verification and validation is applied to the generic hypersonic glide/cruise model.

Each of the model's approximately three hundred physics-based engineering equations are verified by comparing individual results with sample calculations found in Fleeman's textbook, extensive course notes, or in some cases, direct correspondence. The process of modeling and verifying the equations takes several weeks. After verification, the model is then validated.

The model is validated using three baselines (Fleeman 2012):

1. The first baseline is a rocket-powered air-intercept missile, where aerodynamic and propulsion computations are validated by assessing maximum range performance. With this baseline, maximum range is measured for a boost, sustain, coast, glide scenario. This baseline may also be used to measure ballistic range performance where, instead of gliding, the vehicle is left to follow projectile motion after the boost-sustain-coast flight phase.
2. The second baseline is a ramjet-powered cruise missile. Maximum range performance is measured by the Breguet range equation referenced in the MODELING section. This baseline validates all the calculations serving as inputs to the range equation (e.g., aerodynamic lift-to-drag ratio and propulsive specific impulse).
3. The third baseline is a turbojet-powered antiship cruise missile. Again, the Breguet range equation is the performance metric.

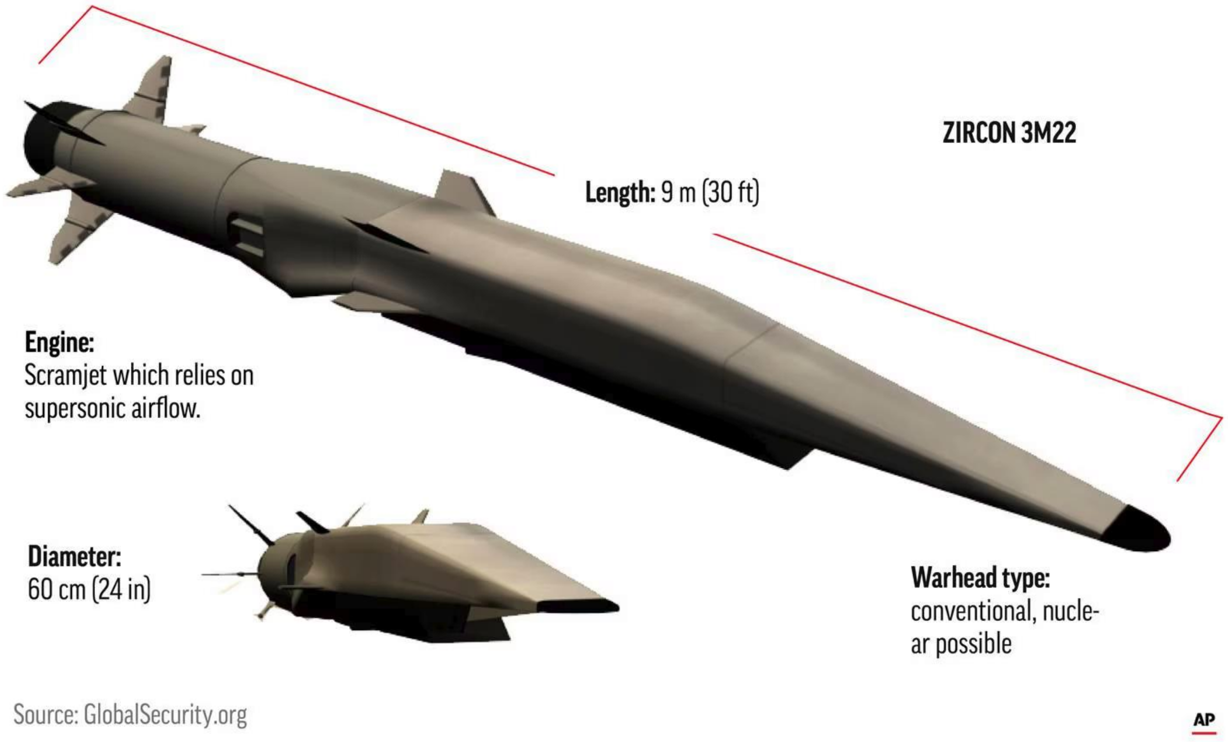
The first baseline scenario most closely represents a hypersonic *glide* vehicle, which is typically boosted under rocket power. Rockets can in fact boost vehicles to hypersonic speeds. After separation, the hypersonic glide vehicle maneuvers to its destination.

Both the second and third baseline scenarios most closely represent a hypersonic *cruise* vehicle. Ramjets operate efficiently at supersonic flight conditions and can operate at hypersonic flight conditions up to approximately Mach 6. These vehicles are boosted with either a rocket motor or a turbojet engine to attain supersonic conditions for the ramjet to begin operation, in a process called "startup." The other major engine type (not yet mentioned) is the scramjet, a supersonic combustion ramjet. This is the current technology used in hypersonic cruise vehicles, and it will be addressed in the FUTURE WORK section.

With a fully verified and validated model (developed on a platform with optimization capability), the threat analyst can maximize range performance (e.g., Breguet in the case of a hypersonic cruise vehicle) and observe the parameters leading to such a solution (e.g., aerodynamic lift-to-drag ratio and propulsive specific impulse) for various conditions (Mach number, weight before cruise, and propellant weight). The details of this type of threat analysis are described in the next section.

SIMULATION

Now that the digital twin model of generic hypersonic glide/cruise vehicles is verified and validated, it allows decision-makers to aggregate threat assessment through simulation. What follows is a threat assessment of Russia's Zircon missile, shown in Figure 1. Note: The data used for this analysis is publicly available from Defense News (2023).



Source: GlobalSecurity.org

Figure 1 – Russia's Hypersonic Zircon (Tsirkon) Missile

The first action is to select a baseline from the model options: rocket-, turbojet- or ramjet-powered. Since Zircon is a hypersonic "airbreather," the ramjet baseline is chosen.

Aerodynamics

The aerodynamic coefficients—namely, coefficient of lift and coefficient of drag, which lead to the lift-to-drag ratio (L/D)—are obtained from a set of equations based on the body geometry and each aerodynamic surface (that is, canards, wings, and tail). Therefore, there is no need to perform computational fluid dynamics simulations which take days or weeks. The model simply needs geometric inputs and aerodynamic surface inputs, which are publicly available and interpretable from Figure 1. Table 3 summarizes the (given) geometric data, and Table 4 summarizes the (interpretable) aerodynamic surface data.

Table 3 – Geometric Data

Body Diameter (in)	24
Body Length (in)	360

Table 4 –Aerodynamic Surface Data

	Wing Section	Tail Section
Mean Aerodynamic Chord (MAC) (in)	9	9
Sweep Angle (deg)	45	10
Span (in)	9	27
Area (in^2)	122	243
MAC Location (in from nose)	234	333

The data in Table 3 is taken directly from Figure 1. The data in Table 4 is estimated by using Figure 1 and scaling it to measure various lengths. For example, holding a ruler to Figure 1, a scale of 30 feet = 7-3/8 inches can be used. Estimating the length (span) of one of the tail sections to be 9/16 inches, produces a scaled tail span of 27 inches (the third entry in Table 3 under "Tail Section"). The other parameters are estimated likewise. Since the geometric parameters are given, these inputs are represented deterministically. In contrast, the aerodynamic surface data is estimated, so their inputs are represented by stochastic variables.

A crucial point to be made here is that the geometric parameters could be stochastic as well. For example, if the length and diameter are not known, one could assess a class of missiles that fit a type of application and use a distribution to represent these geometric properties. Ideally, their impact is measured to see just how much this matters on the overall performance metric. This will be demonstrated in the Sensitivity subsection of the RESULTS section below.

Returning to the topic of lift-to-drag ratio, the aerodynamic coefficients cannot be reported from the geometry or aerodynamic surface data alone because they also depend on the flight conditions: Mach number, altitude, and angle-of-attack.

Propulsion

Propulsive specific impulse (I_{SP}) is obtained from a set of equations based on properties associated with the ramjet engine. Table 5 summarizes the data associated with the specific impulse calculation. Some of these are not determinable, and others are difficult to determine from Figure 1. Therefore, ramjet baseline parameters are used instead. This is why it is important to begin with a relevant baseline for threat analysis.

Table 5 – Ramjet Specific Impulse Data

Fuel Heating Value (BTU/lbm)	Ramjet Baseline
Combustor Fuel-to-Air Ratio	Ramjet Baseline
Combustion Time (sec)	Ramjet Baseline
Combustion Velocity (ft/sec)	Ramjet Baseline
Combustor Flame holder Entrance Area (in^2)	Ramjet Baseline
Inlet Throat Area (in^2)	Ramjet Baseline
Inlet Height (in)	Ramjet Baseline
Inlet Location (in)	Ramjet Baseline

For a ramjet engine, the fuel is typically liquid RJ-5 with a density of 0.037 lbm/in^3 and a volumetric performance of 650 BTU/in^3, yielding a heating value of approximately 17,600 BTU/lbm. This is a driving parameter for specific impulse and impacts range performance.

The other piece of information related to propulsion is the propellant weight as well as the weight of the vehicle before cruise. Since these parameters are currently unavailable, the ramjet baseline values are used.

Flight Conditions

The last set of data needed for threat analysis is the flight conditions. The Wikipedia article (Ref 16) says the operational altitude is 92,000 ft at Mach 9. The angle-of-attack for maximum range is not provided, but the model's optimization platform is leveraged as shown in the RESULTS section below. Note: While Mach 9 exceeds the efficient operation of a ramjet engine (Mach 6), the baseline is the best currently available. Options are addressed in the FUTURE WORK section below.

RESULTS

Having initialized the aerodynamic data (geometry and surfaces), the propulsion data (ramjet baseline), and the flight conditions, the simulation is executed to determine the maximum cruise range. Inputs and outputs that impact the Breguet range equation are summarized in Table 6. To simplify the table, angle-of-attack is represented by α, average velocity is represented by V_{AVG}, fuel heating value is represented by Hf, weight before cruise is represented by W_{BC}, and propellant weight is represented by W_P.

Table 6 – Inputs and Outputs for Threat Range

Mach	Altitude (ft)	α (deg)	V_{AVG} (ft/s)	Hf (BTU/lbm)	W_{BC} (lb)	W_P (lb)
9	92,000	TBD	8707	17,600	4644	449

Currently, the angle-of attack is unknown (see the third column of Table 6), so it is represented by a stochastic variable over a range of values from 0 to 25 degrees. Executing a simulation of the model with this uncertainty in angle-of-attack results in a wide uncertainty range between 48 nautical miles (nmi) and 488 nmi, with a median range of 415 nmi. Hence, there is downside to angle-of-attack uncertainty.

Clearly, the angle-of-attack is not going to be determined from Figure 1, nor is it generally reported in the literature. However, using the optimization platform, it may be determined by maximizing the lift-to-drag ratio for the given flight conditions (Mach 9 at an altitude of 92,000 ft). This results in an angle-of attack of 13 degrees. With this value used deterministically, the range is 492 nmi, with no variance. This is lower than the Wikipedia reported range capability of 540 nmi.

Recall the heating value is set for a baseline ramjet (RJ-5) fuel. The Wikipedia page says the fuel is JP-10. Different varieties of JP-10 fuel with their respective heating values are as shown in Table 7.

Table 7 – JP-10 Fuel Attributes

Variant	Heating Value (BTU/lbm)
40% JP-10, 60% Aluminum	12,028
40% JP-10, 60% Carbon	16,347
40% JP-10, 60% Boron	23,820

By changing the heating value from 17,600 (RJ-5) to a high-performance variant of JP-10 with a heating value of 23,820, the maximum range performance is improved to 652 nmi. The Wikipedia page states further that the Zircon missile can attain ranges from 1000-2000 km (540-1080 nmi). This extra range performance may be picked up with additional propellant weight, different flight conditions, or better fuel.

Before leaving this subsection, note that the optimization platform maximizes the lift-to-drag ratio, thus fixing the angle-of-attack for the given Mach number and altitude (Mach 9 at 92,000 ft, respectively). Also, by introducing a Zircon specialized fuel with higher performance (JP-10), the model simulated maximum range performance within the envelope presented in the Wikipedia article (Ref 16).

Sensitivity

Let's assume there is no knowledge of flight conditions (Mach, altitude, angle-of-attack), heating value of the fuel, or weight of the propellant. Instead, we assume a variance for each parameter as shown in Table 8. For example, Mach number can be anywhere between 6 and 9.

Table 8 – Input Parameter Bounds

Parameter	Lower Bound	Upper Bound
Mach	6	9
Altitude (ft)	1,000	92,000
Angle-of-Attack (deg)	0	20
Heating Value (BTU/lbm)	17,000	30,000
Propellant Weight (lb)	500	1,000

Accounting for all this uncertainty, the median maximum range is 718 nmi and the sensitivities of the inputs are ranked in the Tornado chart of Figure 2. In this figure, lift-to-drag ratio is contributing the most uncertainty to range performance with a low value of -87% (93 nmi) and a high value of +24% (890 nmi). Next is the natural log term (which is a function of the weight before cruise and the propellant weight), then specific impulse, and finally velocity.

Figure 2 – Tornado Chart with Variance of all Inputs

As mentioned previously, angle-of-attack, which is the driver for lift-to-drag ratio, is not going to be reported. Therefore, optimization is leveraged again to maximize lift-to-drag ratio. In this case, however, Mach number and altitude are also allowed to vary. The result is an angle-of-attack of 11 deg at Mach 9 and 28,000 ft yielding a median maximum range of 1,107 nmi (slightly over 2,000 km). From a threat perspective, if the Russians risk flying at a lower altitude (28,000 ft vs 92,000 ft), then cruise range is extended. However, they are probably trading range for survivability.

With angle-of-attack, Mach number, and altitude set to their deterministic values, the remaining uncertainties are propellant weight and specific impulse (fuel heating value). From the Tornado chart of Figure 3, both have approximately the same impact on maximum range performance. Therefore, from an intelligence-gathering perspective, the type (heating value) and amount of fuel (propellant weight) are critical for threat analysis, in addition to a picture of the vehicle.

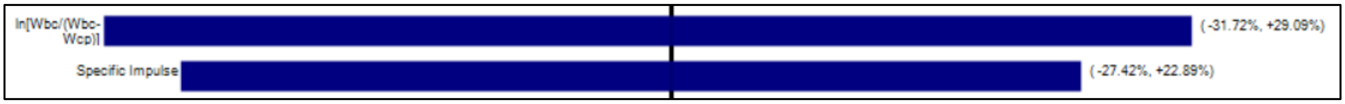


Figure 3 – Tornado Chart with Variance of Remaining Inputs

The conclusion of this subsection suggests using the optimization platform for maximizing the lift-to-drag ratio to fix the three flight conditions (Mach number, altitude, and angle-of-attack). The two remaining parameters (propellant weight and fuel heating value) are to be determined. If the fuel is known (e.g., JP-10), then the last question to answer is “How much propellant is loaded into the vehicle?” If there are limited intelligence assets, this is the parameter to focus on.

CONCLUSIONS

Although there are no programs of record yet, there is a resurgence of hypersonic research and development in the United States. Meanwhile, China and Russia have developed and fielded hypersonic threats (both glide vehicles and cruise vehicles). Because of the inconsistency of U.S. programs, there are fewer knowledgeable individuals to assess these (or other) threats. Therefore, this paper introduced a model to simulate threat analysis to gain valuable insight quickly and inexpensively.

The model is built with over 300 physics-based engineering equations, which are verified and validated with three baselines (rocket-, turbojet-, and ramjet-powered propulsion). Based on multiple iterations of experiments, the results suggest that the ramjet baseline is used to perform threat analysis of Russia’s Zircon hypersonic cruise vehicle. The Breguet range equation serves as the performance metric with inputs of average speed, specific impulse, lift-to-drag ratio, and a factor dependent upon propellant weight. Average speed and lift-to-drag ratio are functions of the flight conditions (Mach number, altitude, and angle-of-attack), while specific impulse is a function of the fuel heating factor.

Results show that the ramjet baseline (in lieu of a scramjet) is adequate for hypersonic cruise vehicle threat analysis. Also, using given flight conditions (Mach number and altitude) and fuel type (heating value), the model computes maximum range performance results in line with reported capabilities. Furthermore, with no knowledge of the flight conditions, sensitivity analysis shows that two parameters—type of fuel (heating value) and amount (propellant weight)—are where intelligence assets should focus.

From a simple photograph, decision-makers can model and simulate threat analyses to determine countermeasures in minutes. Because the aerodynamics are built-up section-by-section, there is no need to run computational fluid dynamics (CFD) simulations over the course of days to amass aerodynamic coefficients. Even without a photograph, a class of missiles that fit a type of application (e.g., cruise missiles) could be cataloged from known data, and statistical distributions could represent geometric properties (e.g., body diameter, body length, and aerodynamic surface properties). Thus, their impact is measured to see just how much this matters on the overall performance metric.

FUTURE WORK

While the ramjet baseline serves as the best option for hypersonic cruise vehicles, a scramjet propulsion system needs to be modeled, verified, and validated for a more complete hypersonic threat simulation. Recall that ramjets operate efficiently near Mach 5 to Mach 6. However, Zircon cruises at Mach 9—exceeding the ramjet operational range. Work has already begun to incorporate the physics-based engineering equations from Heiser & Pratt (1994) and Bertin (1994). Equations for compression, combustion, and expansion have been implemented into the model, including thrust, specific impulse, and efficiencies for performance assessment. Verification and validation are yet to be done.

The SIMULATION and RESULTS sections focused on the Zircon hypersonic *cruise* vehicle. The analysis was based on the cruise portion of Zircon's flight. To get to hypersonic speed, of course, Zircon is boosted with a solid rocket motor like hypersonic glide vehicles. While the model has a separate rocket-powered baseline, rocket propulsion will be integrated with other propulsion baselines (turbojet, ramjet, and scramjet) to form what is called multistage propulsion. For example, one system might be an airbreathing multistage propulsion concept beginning with the turbojet (0-2 Mach), transitioning to the ramjet (2-5 Mach), and finally the scramjet (5-X Mach). This is similar to the single-stage-to-orbit (SSTO) X-30 National Aerospace Plane mentioned in the INTRODUCTION.

After integrating all propulsion options, aerodynamics will be integrated so that there is interdependence between the subsystems. This is important with hypersonic vehicles because the shape of the body is part of the propulsion system, where the forebody serves as the inlet, and the aft body serves as the expansion nozzle. With the integration of these subsystems the platform enables Multidisciplinary Design Optimization: a process to simultaneously account for geometric trade studies for aerodynamics and propulsion.

Finally, from a logistics perspective, imaging obtained by various platforms needs to be integrated with *a priori* knowledge to assess performance faster than time to impact.

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