

AIM-54 Simulation

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Heatblur Simulations

Introduction

We were contracted by Heatblur to provide CFD and Simulation Data for a simulation of the AIM-54 Phoenix Missile for the upcoming DCS: F-14 Tomcat module.

The initial step was a large data mining exercise to gain as much information on the weapon as possible. We used a combination of both publicly available and restricted (but not classified) sources as well as information provided by Heatblur in their own research endeavours and from subject matter experts.

Firstly missile characteristics are needed to not just get a feel for how the missile should behave, but specifics about its fuel weight, thrust and burn time, center of gravity, etc. Courtesy of Heatblur and their own research efforts, scan data of a live AIM-54 was provided. This was converted in Solidworks into a 3D model. This lays the groundwork for us to begin simulating the missile.

The second and equally as important data is live and/or simulated performance envelopes from credible third parties. Such sources as the US Naval Postgraduate School and NASA's Dryden Flight Center. These give an independent comparison to validate our simulation and help improve the flight model as necessary.

Once the 3D model was generated in Solidworks, it was imported into Ansys' Fluent package to simulate. We were commissioned to perform simulations at level flight (0 AoA) for 6km and 12km altitude; these altitudes were chosen as these are the most likely altitudes the missile will be fired from. We performed 5 different velocity (M1.1 - M4) simulations at these altitudes to provide reasonable accuracy for drag modelling. Multiple AoA's were offered to provide a fuller picture of the missiles behaviour in maneuvered flight, but was rejected on the grounds of cost saving and engine limitation.

The data was exported into excel and drag curves were generated. This provides two accurate regimes of flight performance. To expand this picture we changed the atmospheric modelling to extrapolate the expected drag above and below the simulations. This grants reasonable accuracy for other altitudes, although should be used with caution.

Using the simulated velocity/time graphs, trial and error was used to adjust a new missile's flight model to match. Due to subtle differences in the DCS atmosphere engine compared to the idealized atmosphere in the simulation there are slight variances but we are happy with the end result.

This prototype flight model was then tested against known real life drone intercepts from the USN which demonstrated the accuracy of the flight model. The flight model performed well against the literature, however the missile guidance was the biggest shortcoming. The missile's loft logic is very simplistic and the maximum loading had to be artificially limited to 7g in order retain appropriate energy during lofted climbs. These drawbacks are due to limitations in the DCS engine for missile guidance and countermeasure interaction. We will continue to work in consort with Heatblur to adjust missile parameters once these changes are implemented.

Missile Description

We will skip a lot of the basic information that can be easily accessed on Wikipedia and move directly to the more ambiguous and pertinent history and data of the Phoenix.

When the AIM-54A entered production in 1960's, Hercules was awarded the contract to produce the Mk47 Mod 0 rocket motor.^{[1][4]} However on delivery they found the motors had substandard reliability. Aerojet was contracted to produce a motor in tandem to supplement, producing the Mk60 motor. The Mk60 motor was larger and used a slightly different fuel than the original Mk47. The AIM-54A entered service in 1974 with the USN. In 1978 Aerojet's contract with Hughes expired.^{[1][4]}

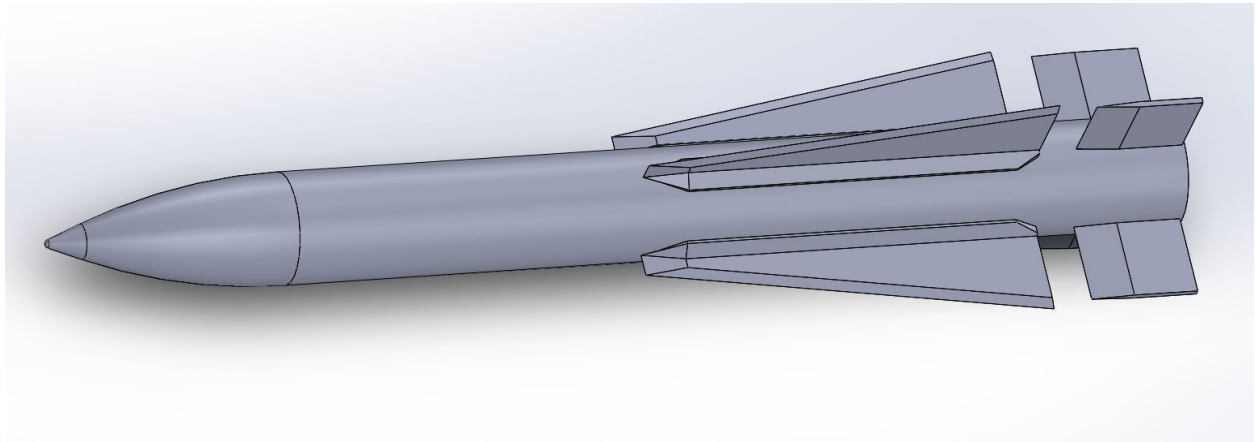
Due to increased usage of electronic warfare, the AIM-54 got an upgrade in the 1980's to the AIM-54C. This included new guidance electronics to improve low level, tight formation cruise missile intercepts, as well as new lofting algorithms. The new ECCM suite required a plumbed coolant system which increased the weight of the missile. Hercules also upgraded their Mk47 motor to the Mod 1, which includes the new smokeless HTPB propellant.^{[1][4]}

Missile Designation	AIM-54A	AIM-54A	AIM-54C
Missile Diameter, cm	38.3	38.3	38.3
Missile Length, cm	401.3	401.3	401.3
Missile Weight	447.7	471.7	465.6
Rocket Motor Designation	Mk47 Mod 0	Mk60	Mk47 Mod 1
Rocket Motor Weight, kg	201.3	256.1	201.3
Rocket Fuel Weight, kg	163.3	208.2	163.3
Propellant Type	Flexadyne	CTPB	HTPB
Thrust, N	14,951.8	17,020.4	15,723.1
Burn Length, s	27	30	27
Isp	252	250	265
Smoke?	High	Medium	"None"
Warhead, kg	60.68	60.68	60.68

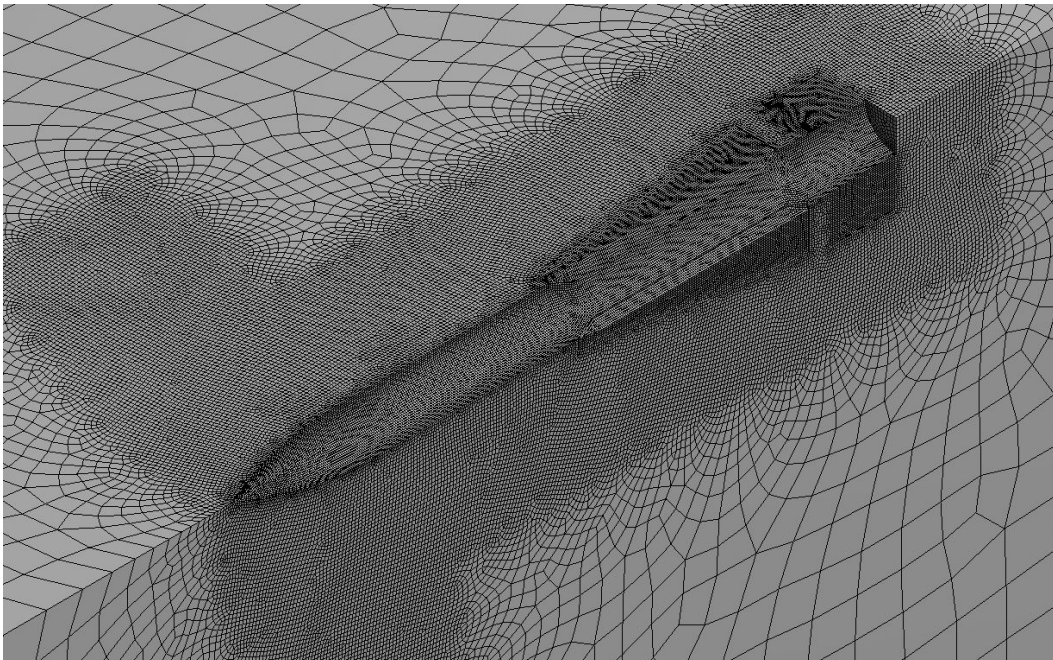
AIM-54 specification table^{[1][2][3][4][5][6]}

Simulation Description

We created the 3D model based on reference materials available to us, then used it to create a flow domain that surrounds the missile during flight. To reduce the computational costs of the simulation we used a quarter model approach for our modelling. During the positioning of the model in the flow domain we had to consider what boundaries are coincident with the symmetry planes. Our tests showed that placing the fins inside the flow domain versus placing it on the boundary provided better stability and faster convergence during the simulations.

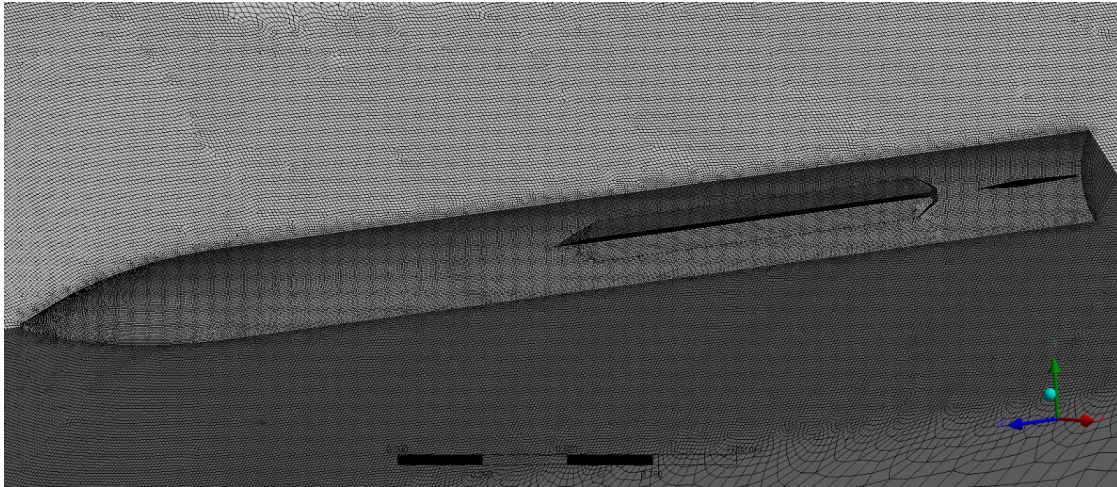


CAD model used for creating the flow domain

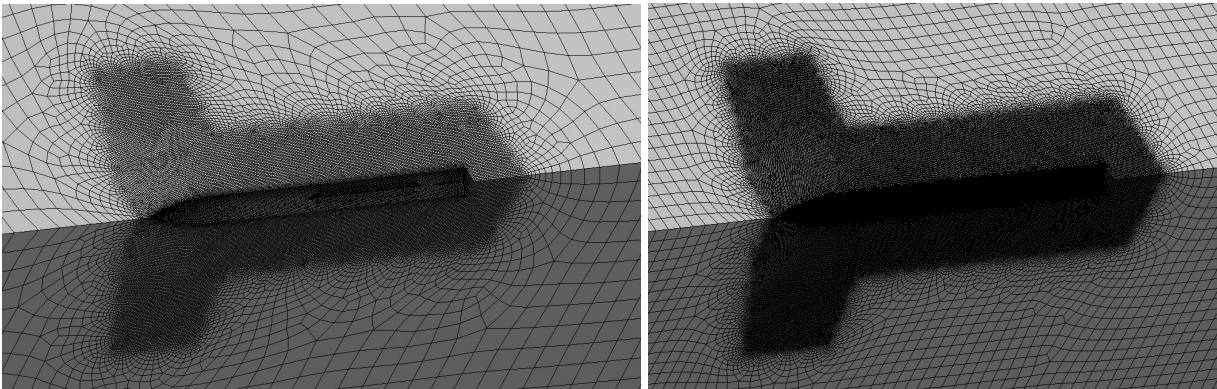


Mesh configuration with the fins coincident with the symmetry planes

The missile is surrounded by a two step mesh: the first layer is for the boundary resolution required by the wall treatment model, the second one is for resolving any possible shockwaves next to the missile body, with focus on the main bow shock. We also added a dissipative layer at the outside mesh boundary to damp possible shock-wave reflections.



Final mesh configuration with the fins inside the flow domain



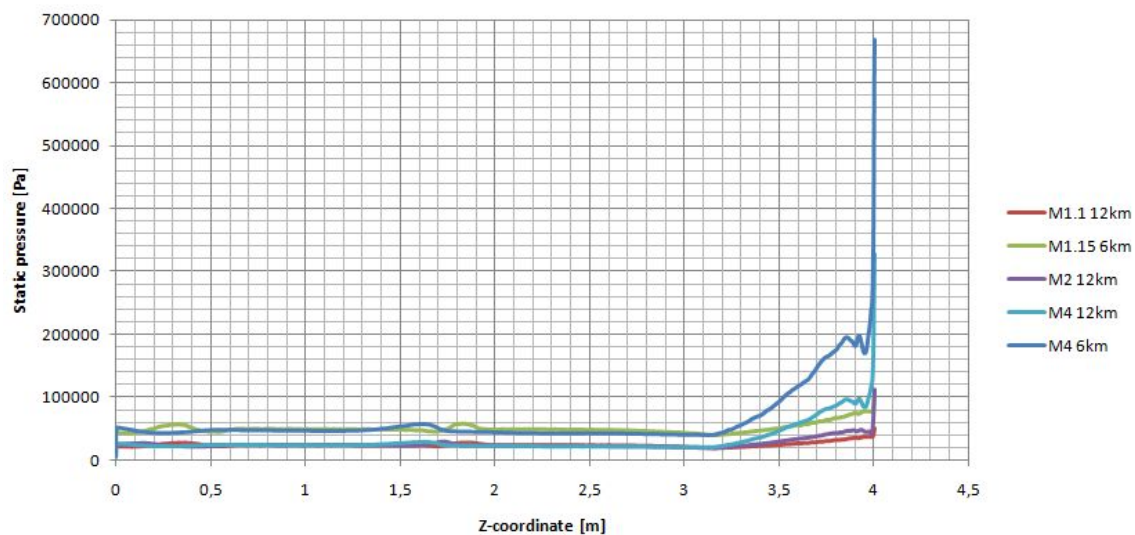
Mesh sensitivity study: mesh density difference

To make sure the mesh is not limiting our results, we carried out a mesh sensitivity study, based on which we selected the final sizing for the cell distribution that resulted in 2 958 953 hexahedron cells. One limitation that remained in the simulations is that we could only simulate supersonic velocities safely (hence no Mach No=1 case). This is due to a singularity in the simulation model that we used which is inherent in these kinds of numerical simulations, unless treated with numerical tools specific for a given case.

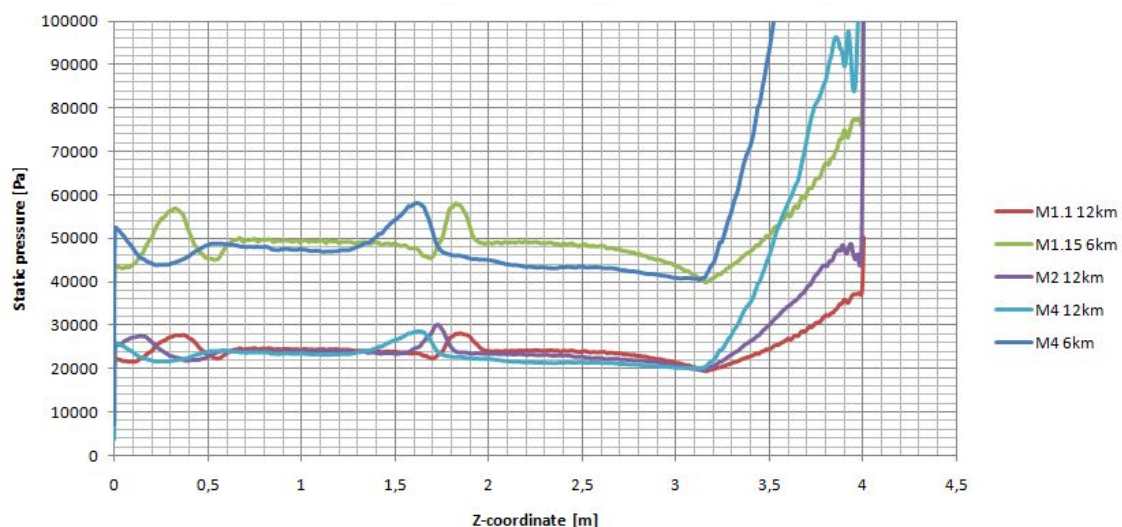
The simulations used the density based finite volume solution method of the Navier-Stokes equations, achieving closure using the k-omega SST RANS turbulence and wall model. The simulations use a small amount of over-relaxation to dampen the initial fluctuations and feedbacks created by the sudden onset of the shock-waves.

Simulation Results

We obtained results on two altitudes and at five velocities at each altitude. Below we can see the pressure distributions for a few selected cases. We can observe the large static pressure peak at the ram-point of the missile and the high pressure zone of the nose cone on the right side of these graphs. Zooming in we can see the separate pressure peaks created by the shock-waves of the wings then, downstream of that, the fins'. We can also see from the downstream-shifting nature of these peaks, that with the increasing velocity the angle of the oblique shock waves forming at these points also increases.

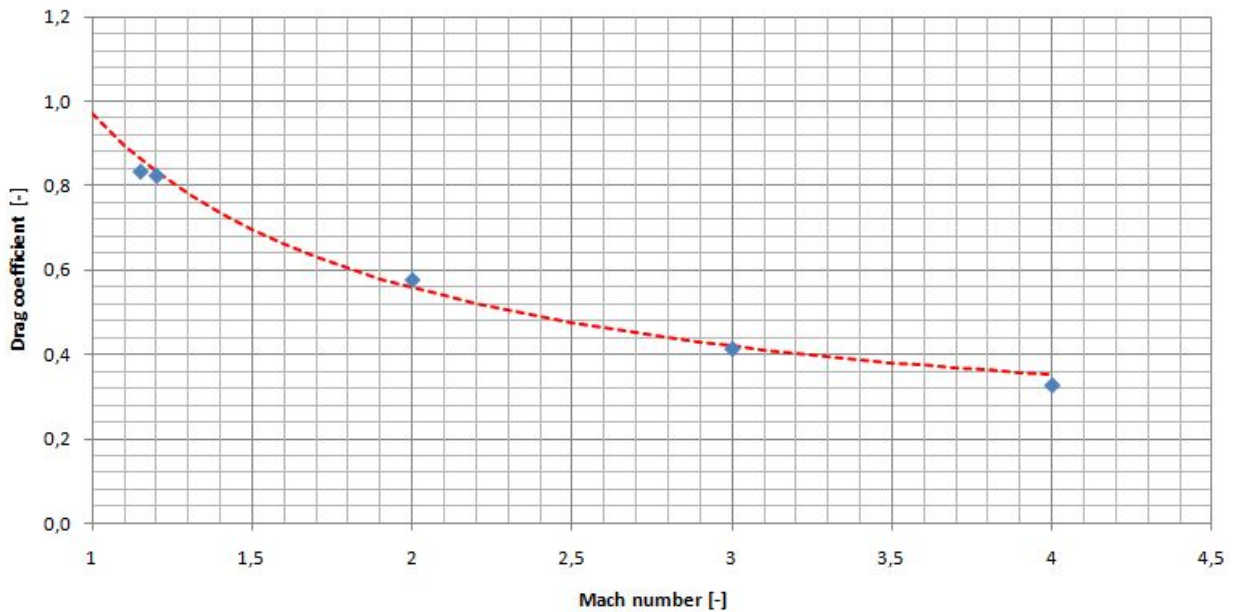


Pressure distribution along the missile body

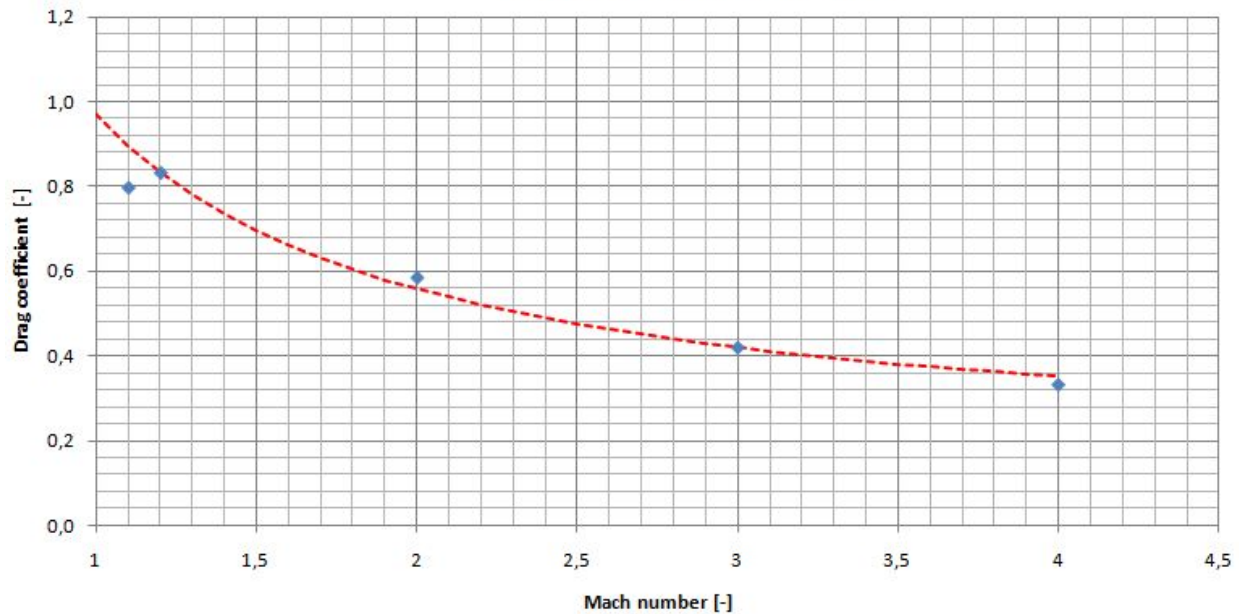


Pressure distribution along the missile body: Detail of the secondary shockwaves

We calculated the drag forces from the combined surface integral of the face-normal forces and face-shear forces on the whole missile surface. From these we calculated the drag coefficients at each altitude and fitted a curve that uses the same trajectory as the game engine does. We used this function to further calculate the flight profile of the missile in level flight and in a loft scenario. This simulation is considerably simpler than the one used for the AIM-120, but in this case we do not have drag data for flight at AoA.



Drag coefficient at 6km



Drag coefficient at 12km

Processed Results

A missile flight model was created using the default missile AFM code to match the simulated data. This process was done through trial and error, initially starting at the simulated 6km and 12km altitude. Once the missile flew through both regimes as per the simulated curve, experiments were done at higher and lower altitudes. As the altitude decreased the AFM matched the simulation's extrapolated results, as seen in the 500m graph. There is slight variation between the simulated curves and the ingame curves, however this is a tacview export which gives rounded numbers of what the game engine actually generates. As the altitude increased beyond 12km the curve diverges slightly, where the simulation expects the missile to slow down faster than the game engine. This is likely a fault on the simulation's atmosphere modelling as gas constant values change. NASA's AIM-54 performance at >16km actually outperforms both the simulated and ingame modelling^[6].

Once we were happy with the curve for level flight, the missile was then tested against known^[5] shots performed by the USN in testing. In order to achieve these hits with reliability, the variables that govern missile lofting had to be adjusted. Due to limitations in the engine, this included reducing the missiles maximum g loading to 7; which according to the USN is far below the demonstrated 18g capability of the AIM-54A^[5]. This compromise was necessary however in order to ensure the missile made the long range intercepts it is known to achieve.

Known shots

1. High Altitude Intercept^[5]
Target - 72,000ft, M2.8. Launcher - 41,000ft, M1.12. Range 51nmi.
Result: Intercepts regularly, however the highest altitude we could get an AI to fly was 68,000ft.
2. Sea Skim Intercept^[5]
Target - 50ft, M0.75. Launch 10,000ft M0.72. Range 22nmi.
Result: Intercepts regularly, although at subsonic speeds.
3. Maximum Range Intercept^[5]
Target - 52,000ft, M1.55. Launch - 45,000ft, M.145. Range 110nmi.
Result: Intercepts irregularly, largely due to missile guidance logic.
4. Multi-Target Intercept^[5]
6 Targets - 20,000 - 23,000ft at M0.5 to M0.8. Launcher - 28,400ft M0.8. First Launch at 50nmi, final launch at 32nmi. (4 of 6 missiles hit)
Result: Hits regularly. The F-15 can only lock 4 targets simultaneously and locking 4 targets in close formation at range is challenging. Nevertheless, in tests, typically 4-6 targets are intercepted.

Summary

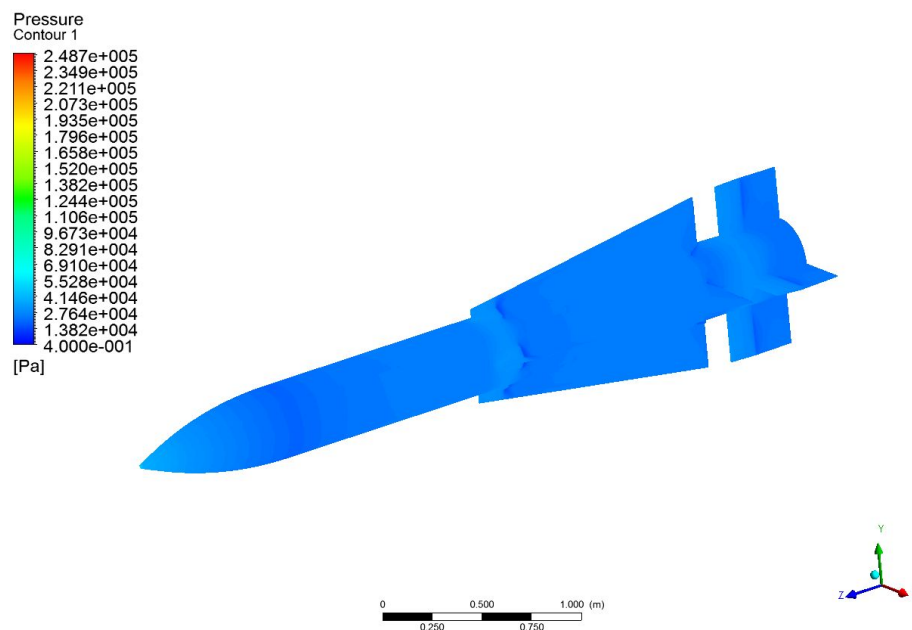
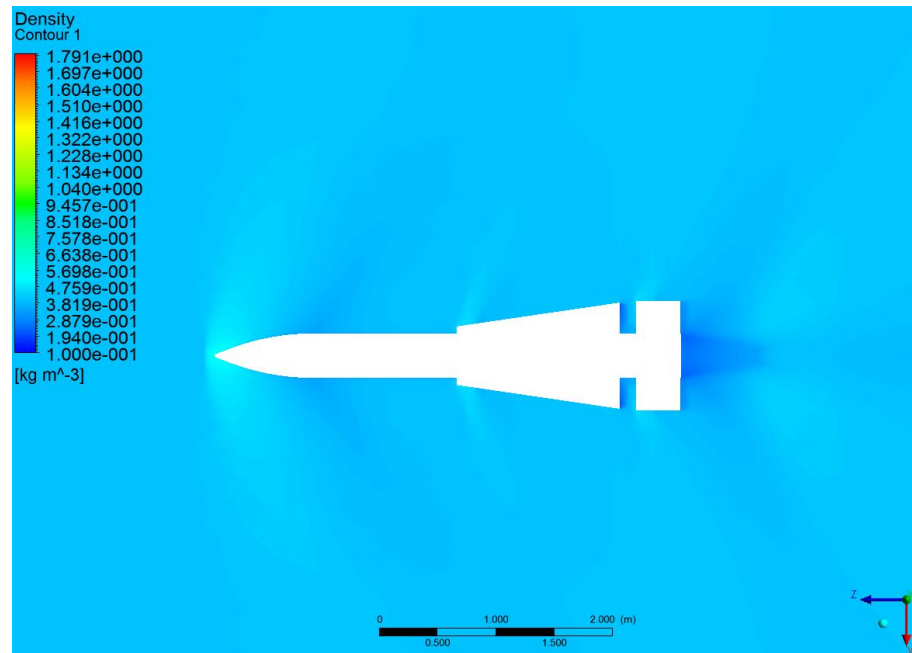
The final result provides Heatblur Simulations with a missile flight model that is based on numerical fluid dynamics simulations with a complexity within the realms of not yet diminishing returns. We feel that considering the available tools to modify the in-game behaviour of a missile's flight this is as good as one can get. In the event more restricted data is released which contradicts any data shown below, adjustments will be made accordingly.

References

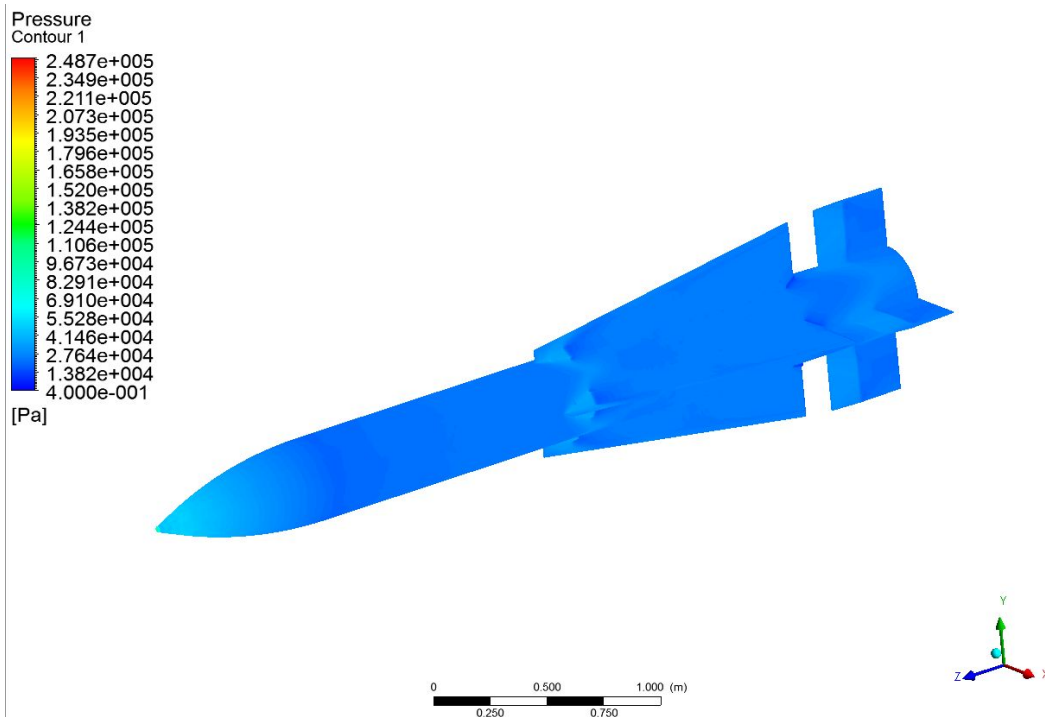
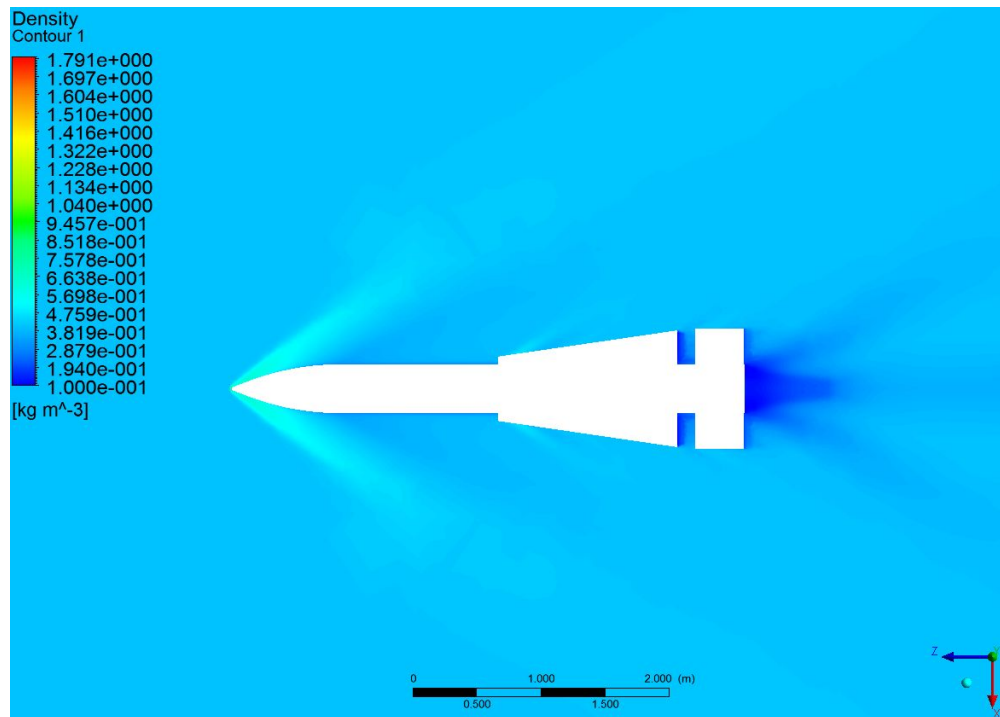
1. Missile Forecast, AIM-54A/C/C+ Phoenix, Forecast International, November 1997
2. AD-A142-508, Weapon File, USAF, June 1984
3. Hazard Classification Of United States Military Explosives and Munitions, U.S. Army, June 2009
4. Solid Propulsion Enabling Technologies and Milestones for Navy Air-launched Tactical Missiles, AIAA 2011-6941, Thomas L. Moore, September 2011
5. An Outsider's View Of The Phoenix/AWG-9 Weapon System, Stephen Thornton Long, Naval Postgraduate School, March 1977
6. Phoenix Missile Hypersonic Testbed, Thomas Jones, Nasa Dryden Flight Research Center, March 2007

Appendix

Simulated Results

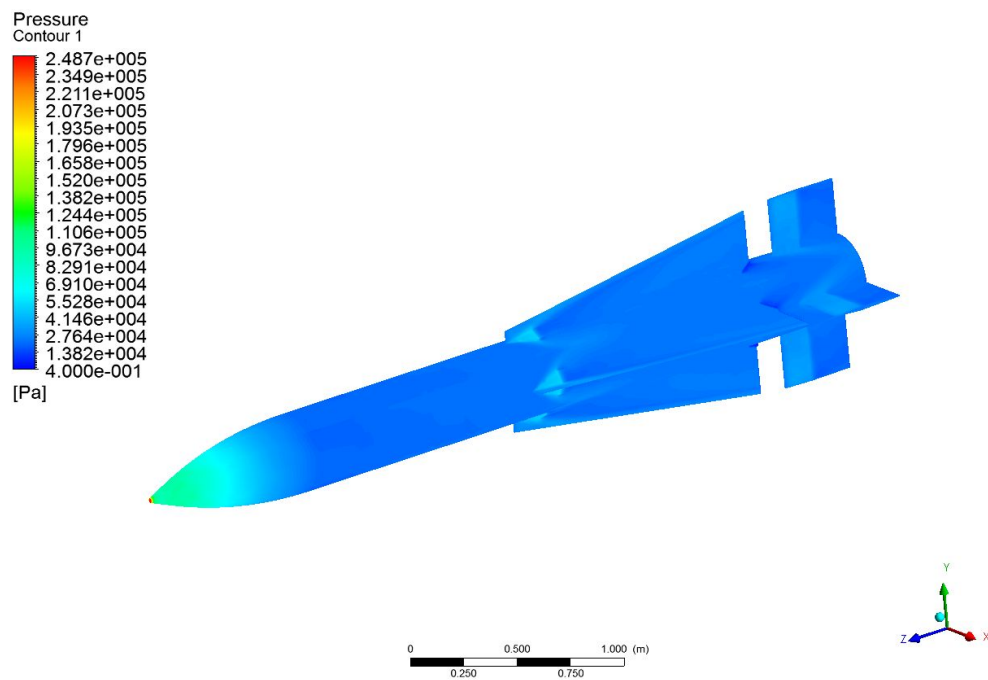
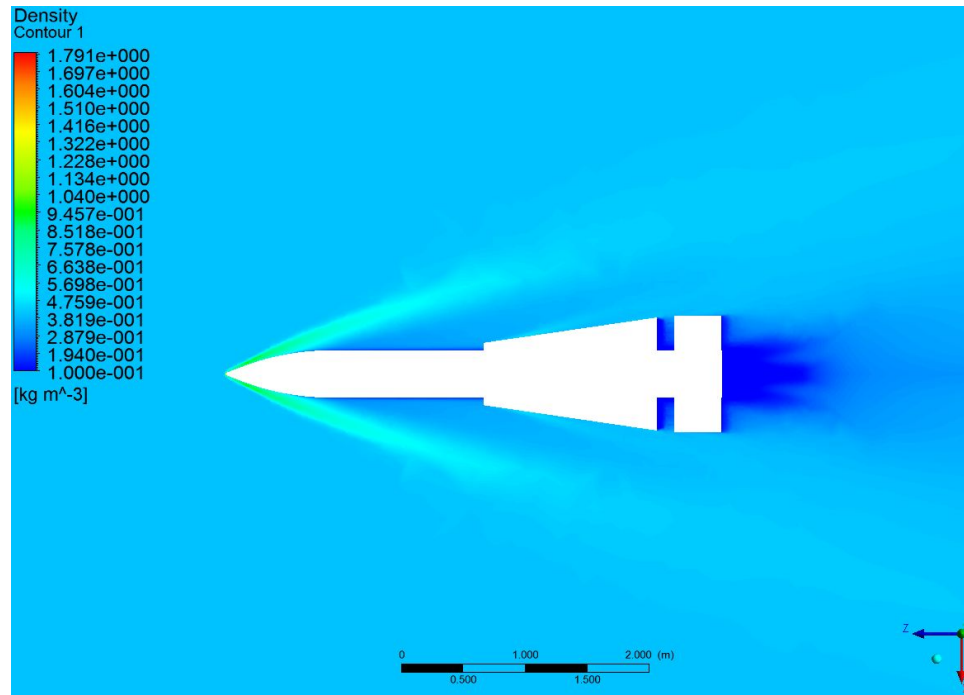


M1.15 12km

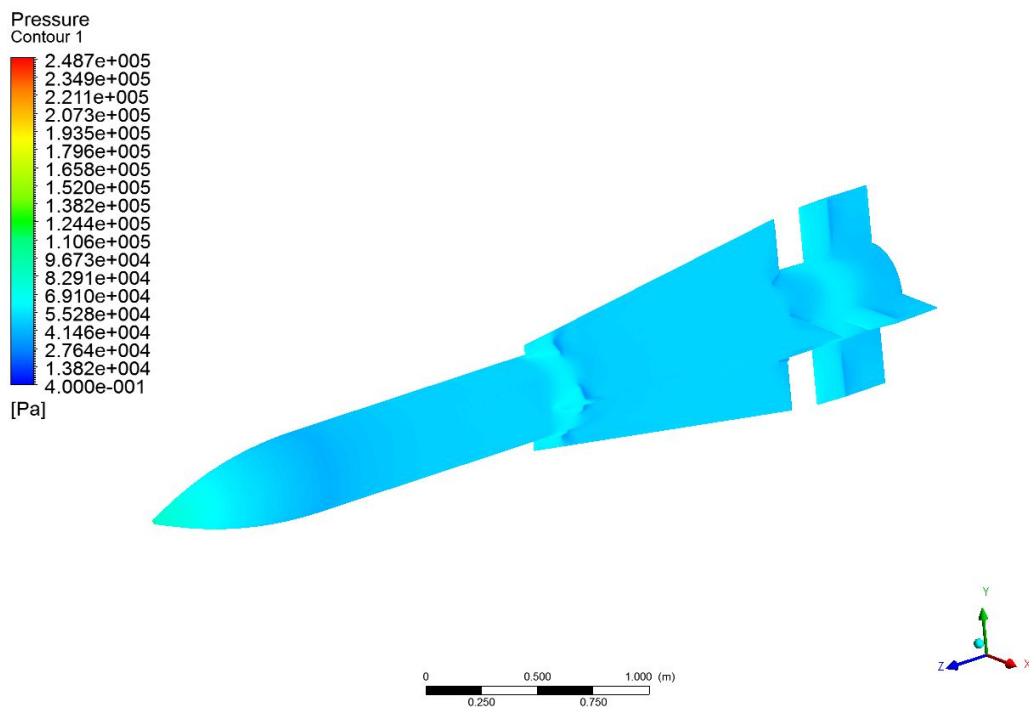
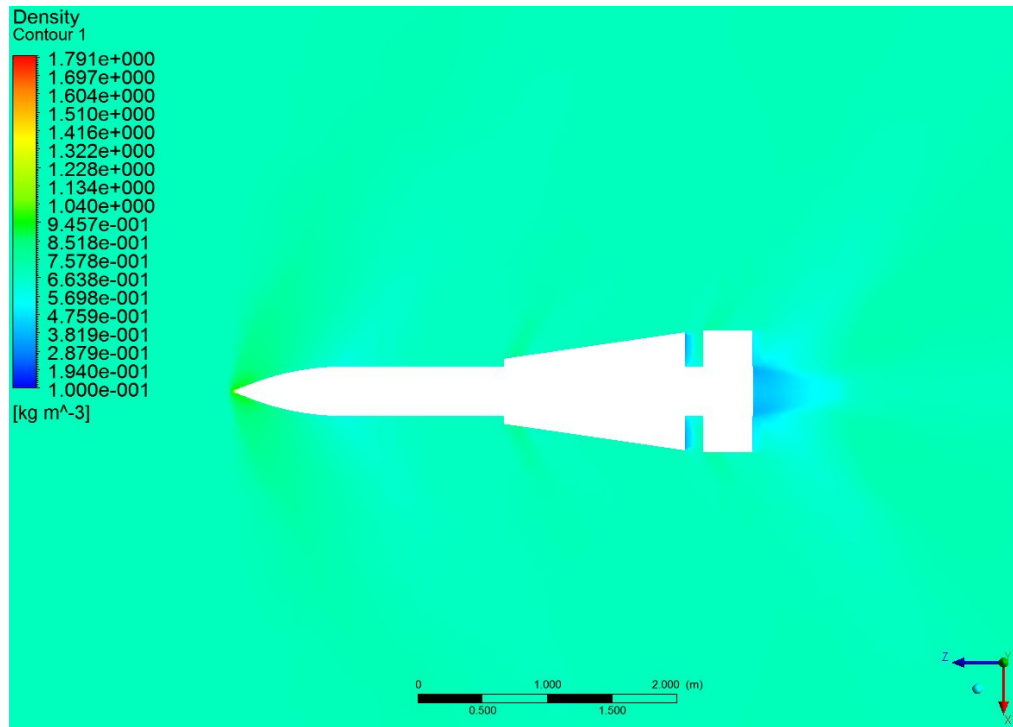


M2 12km

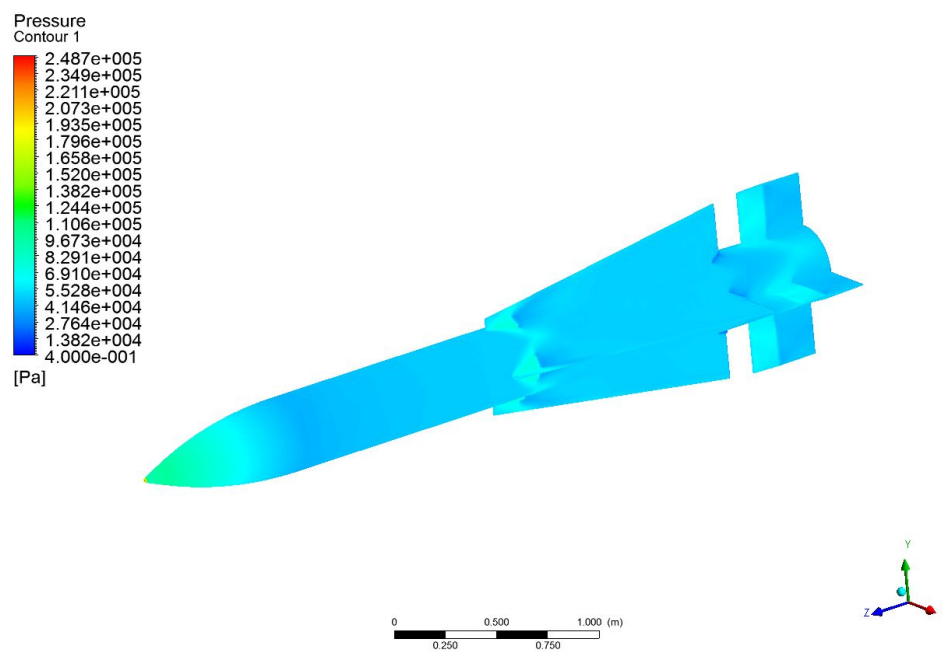
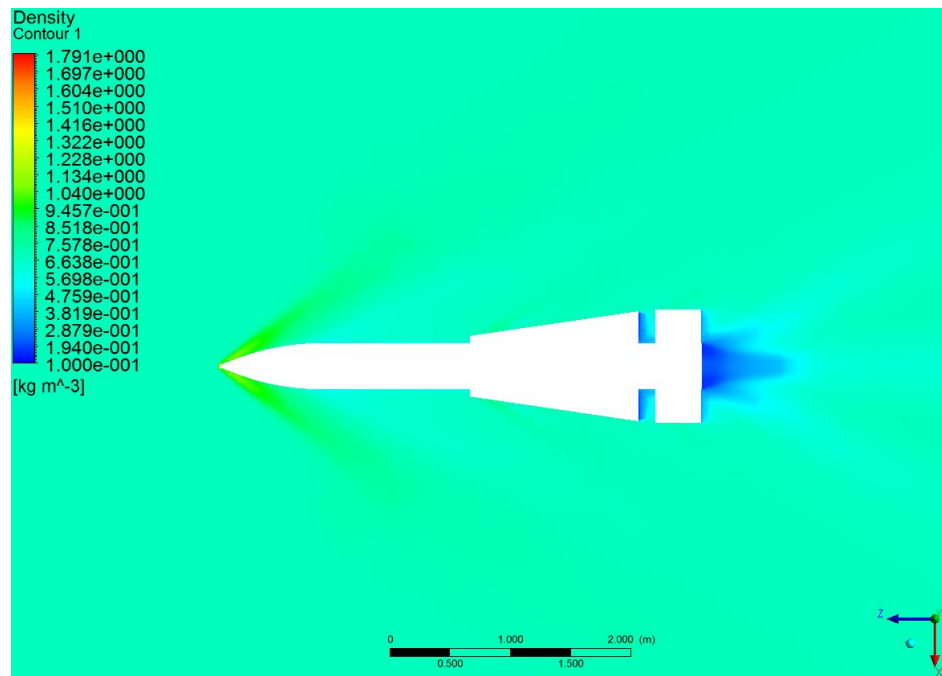
Heatblur Simulations



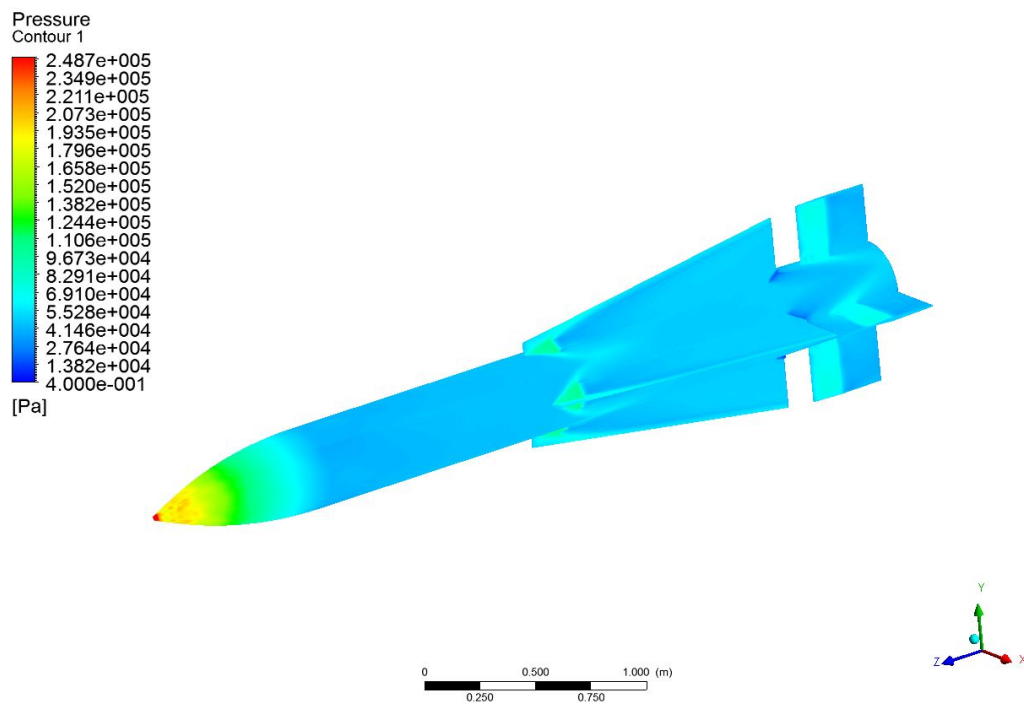
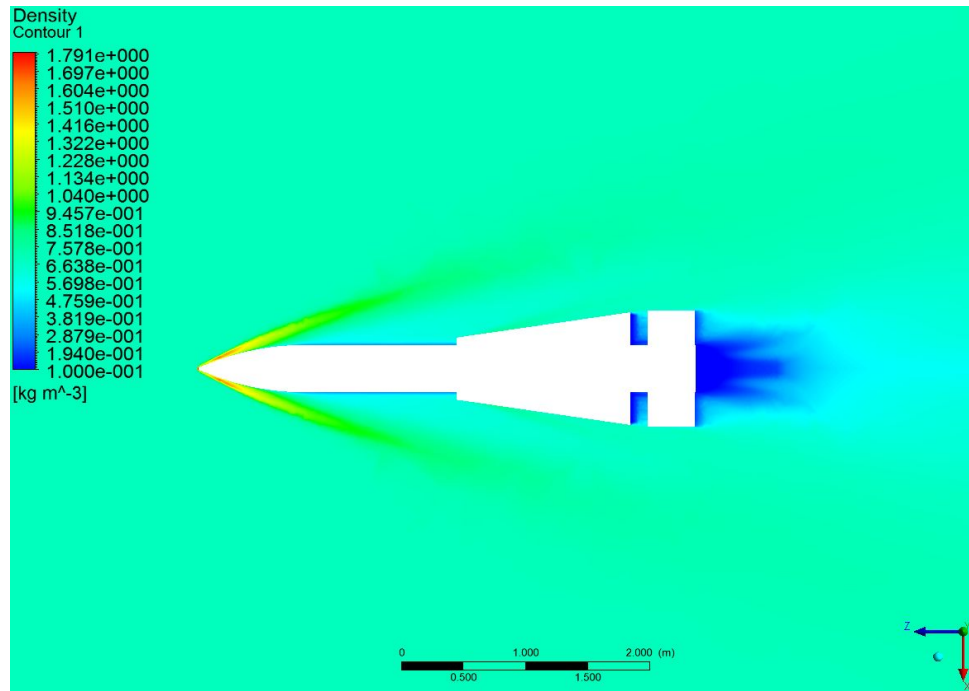
M4 12KM



M1.15 6KM



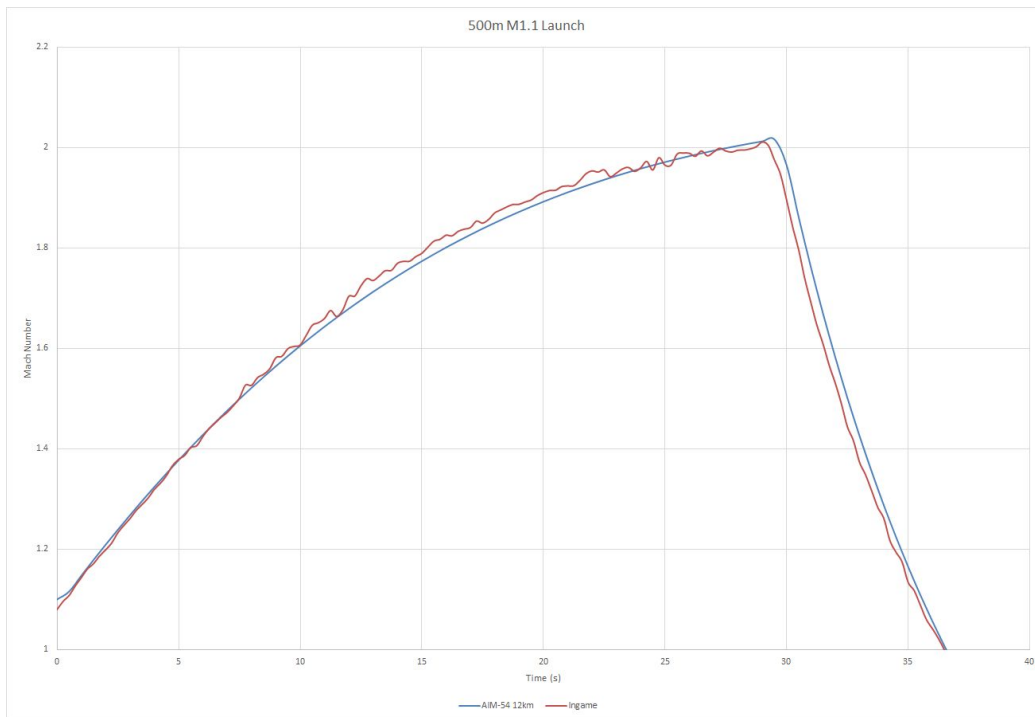
M2 6KM



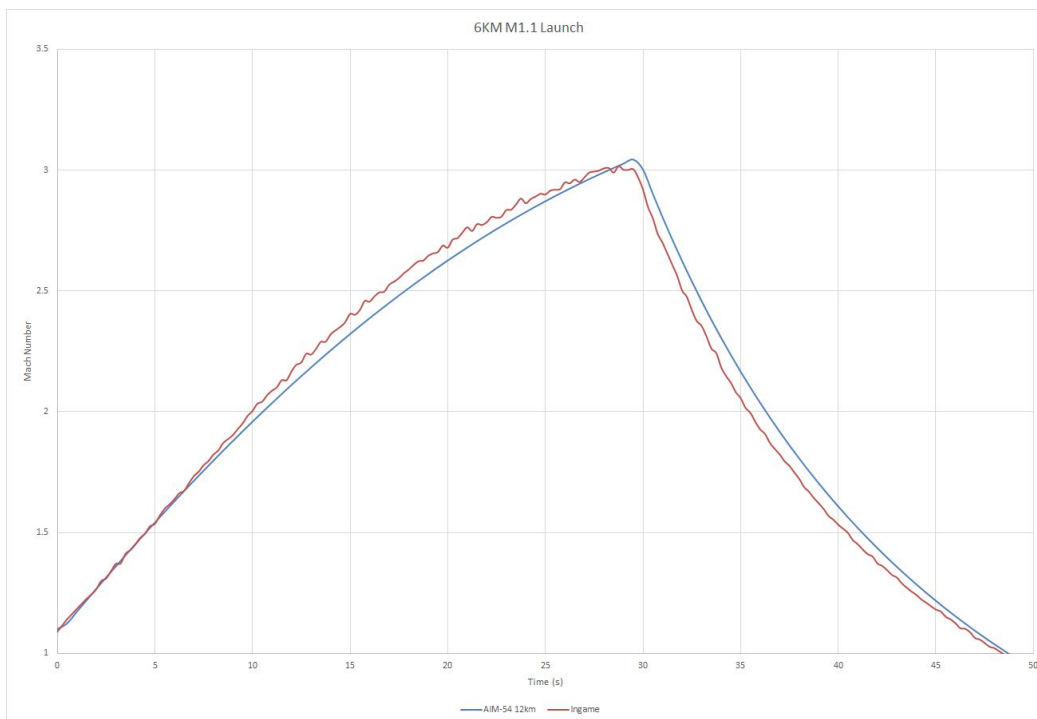
M4 6KM

Heatblur Simulations

Processed Results

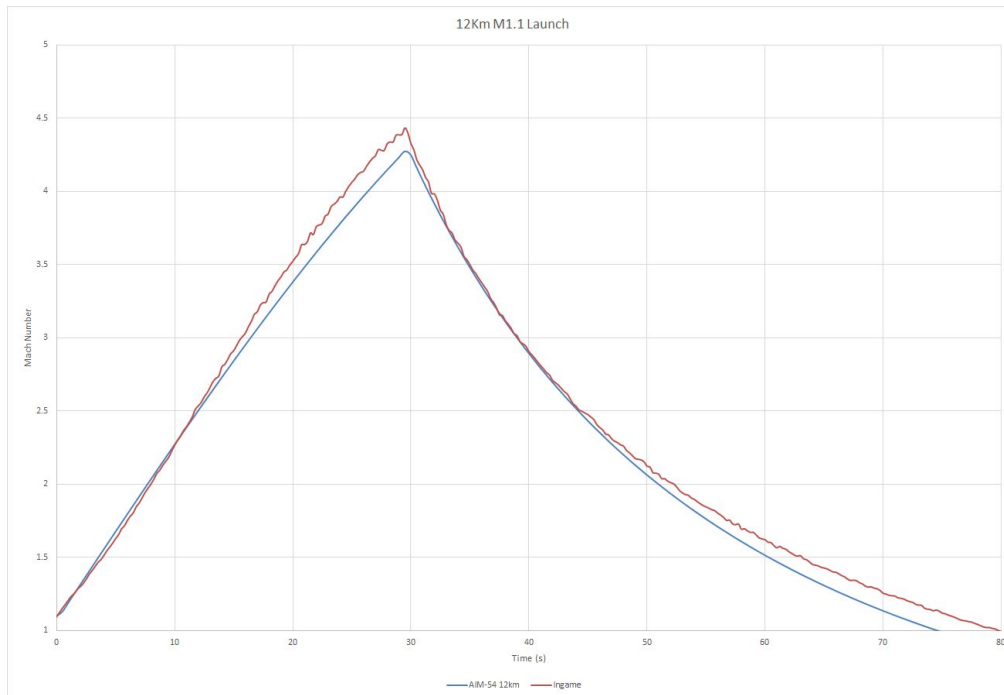


500m simulation vs. flight model comparison

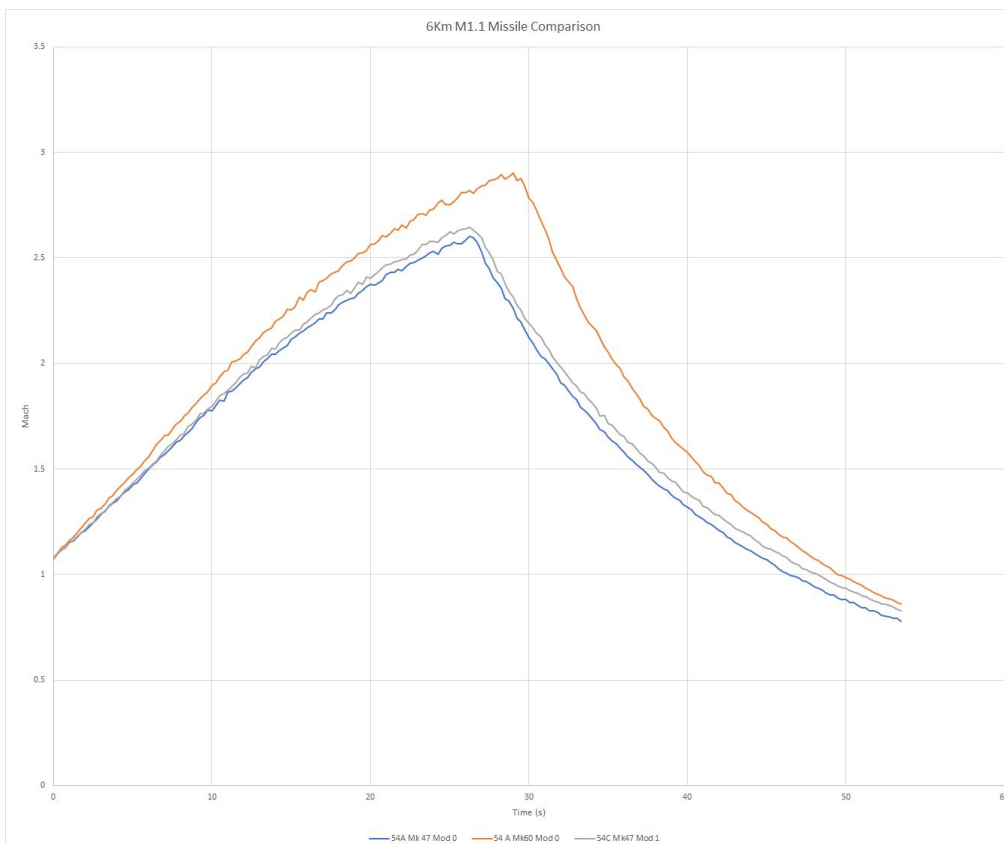


6km simulation vs. flight model comparison

Heatblur Simulations



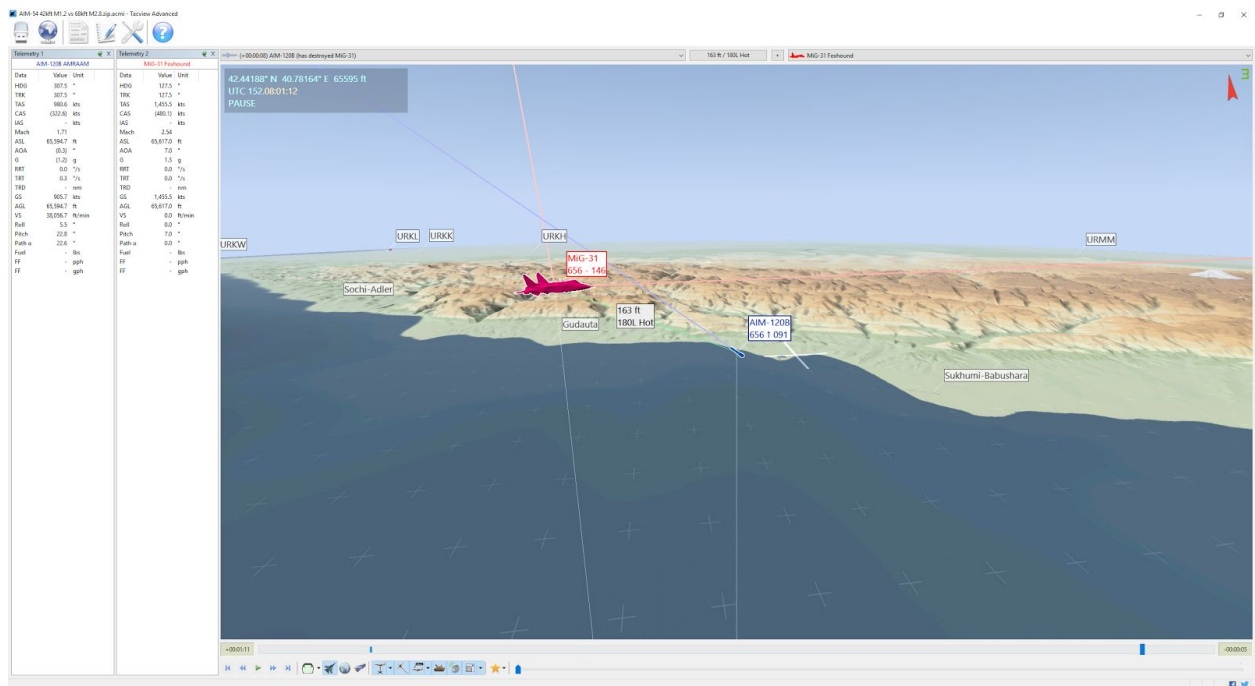
12km simulation vs. flight model comparison



6km comparison of the three AIM-54's

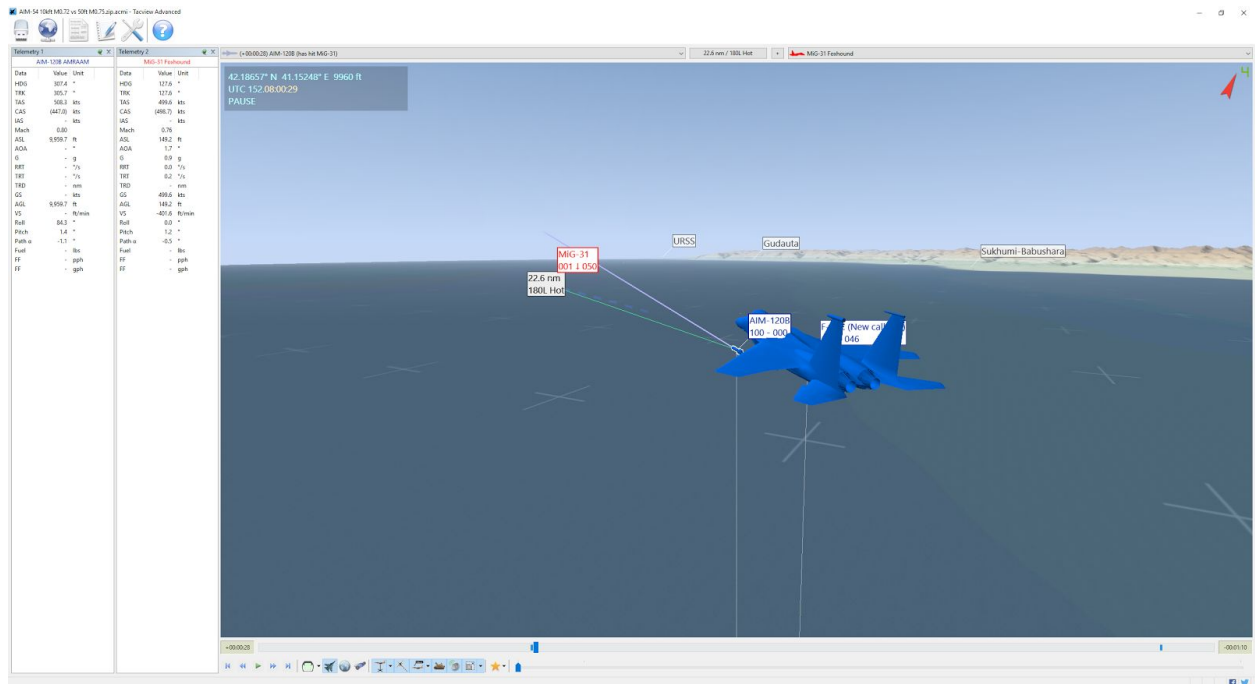


High Altitude Intercept Launch

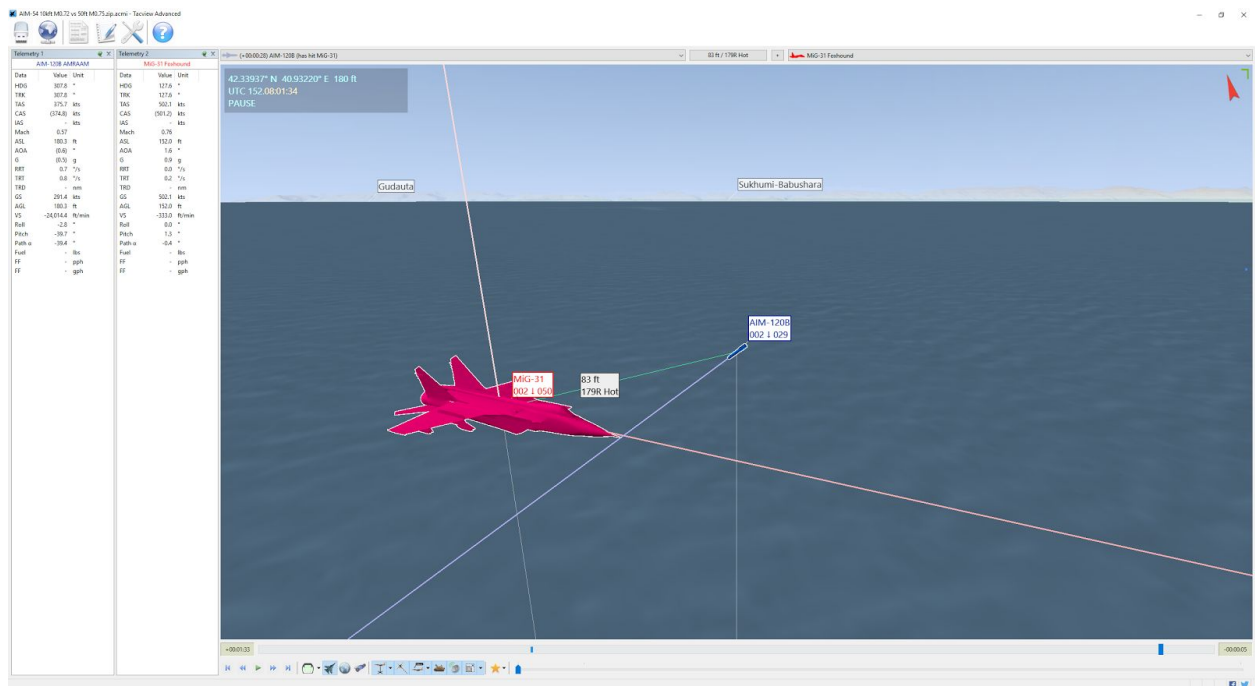


High Altitude Intercept Hit

Heatblur Simulations

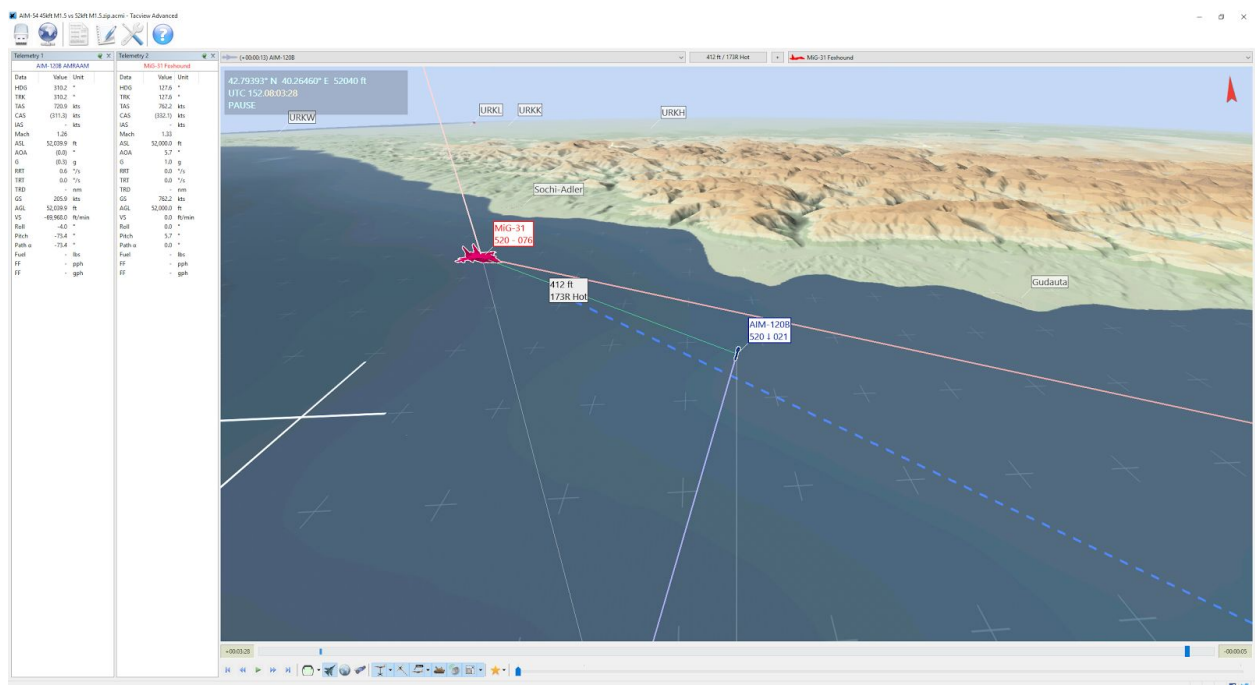
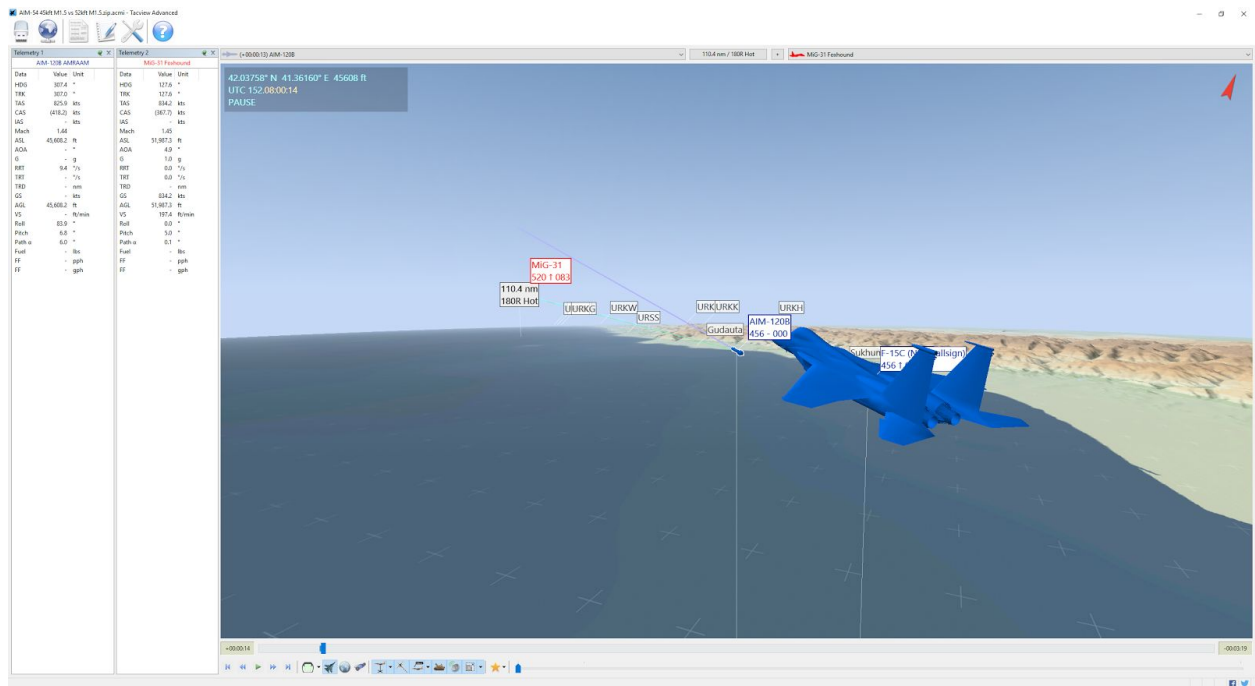


Sea Skim Intercept Launch

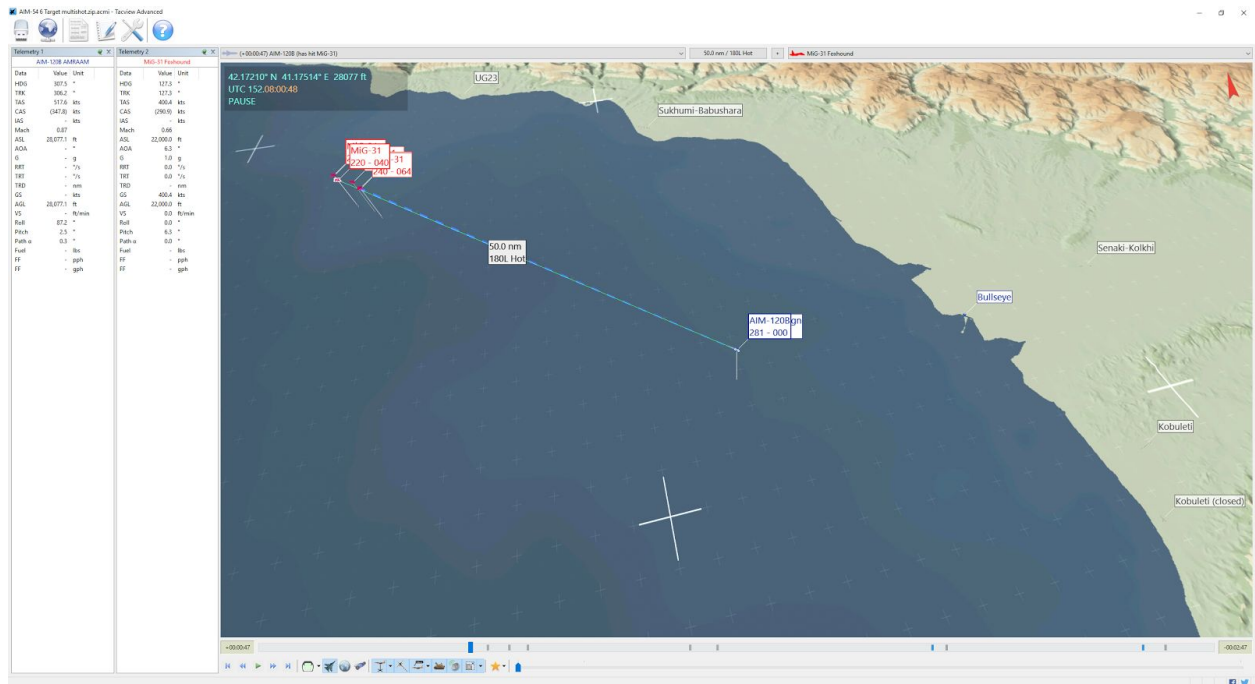


Sea Skim Intercept Hit

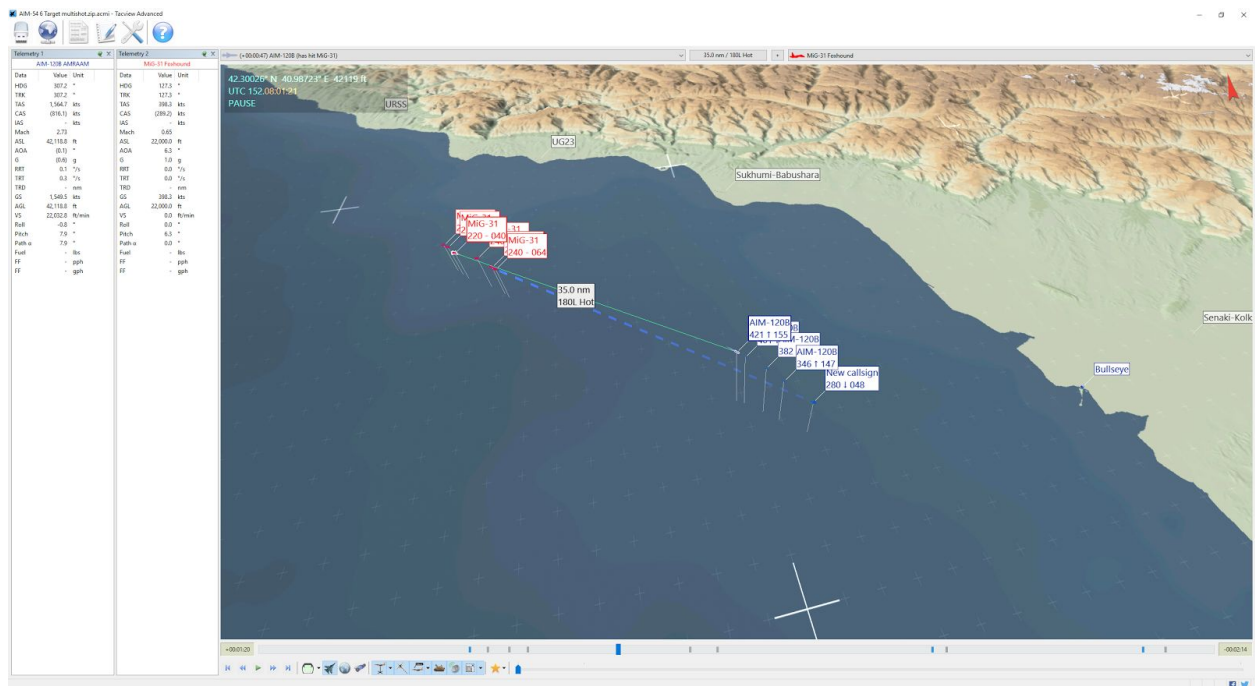
Heatblur Simulations



Heatblur Simulations

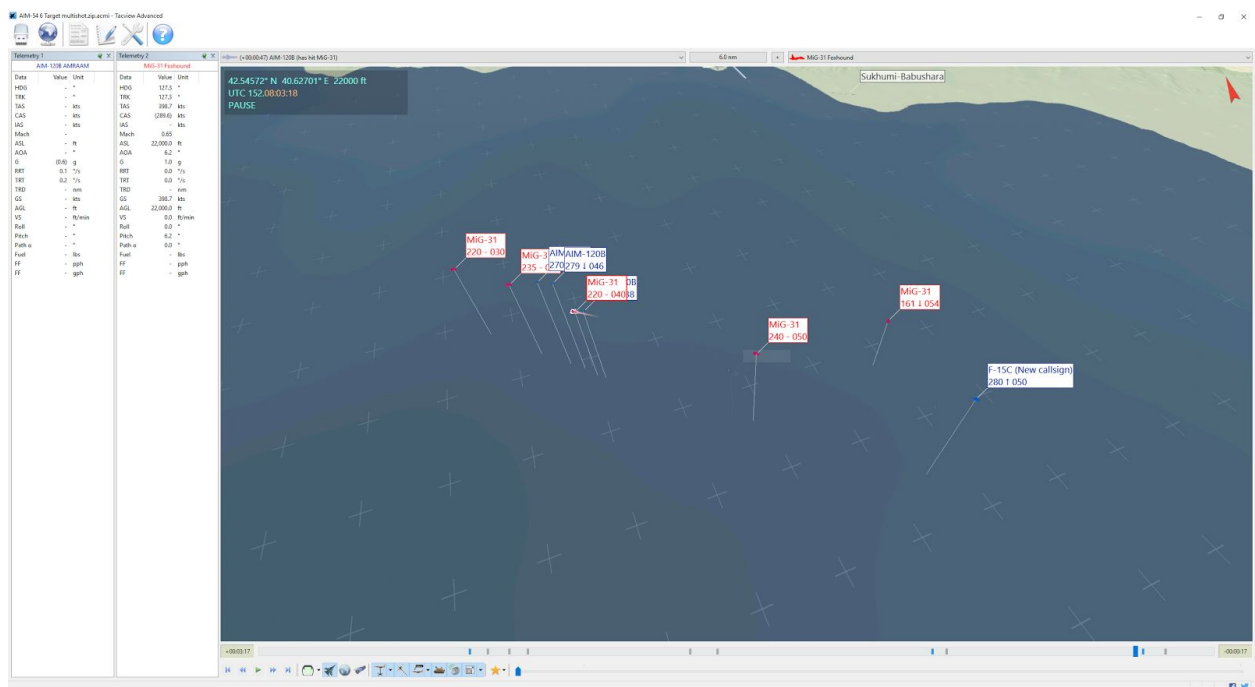
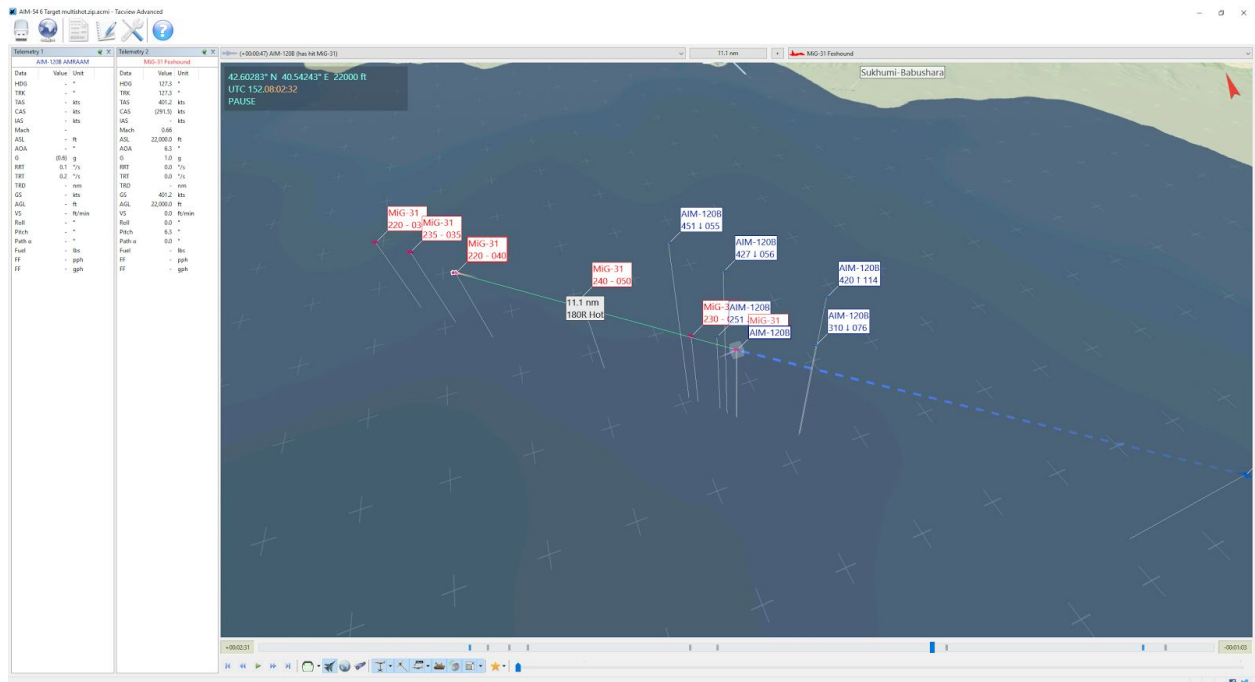


Multi-Target Intercept Launch



Multi-Target Intercept Mid-Flight

Heatblur Simulations



Multi-Target Intercept Hits

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