

Powering Innovation That Drives Human Advancement

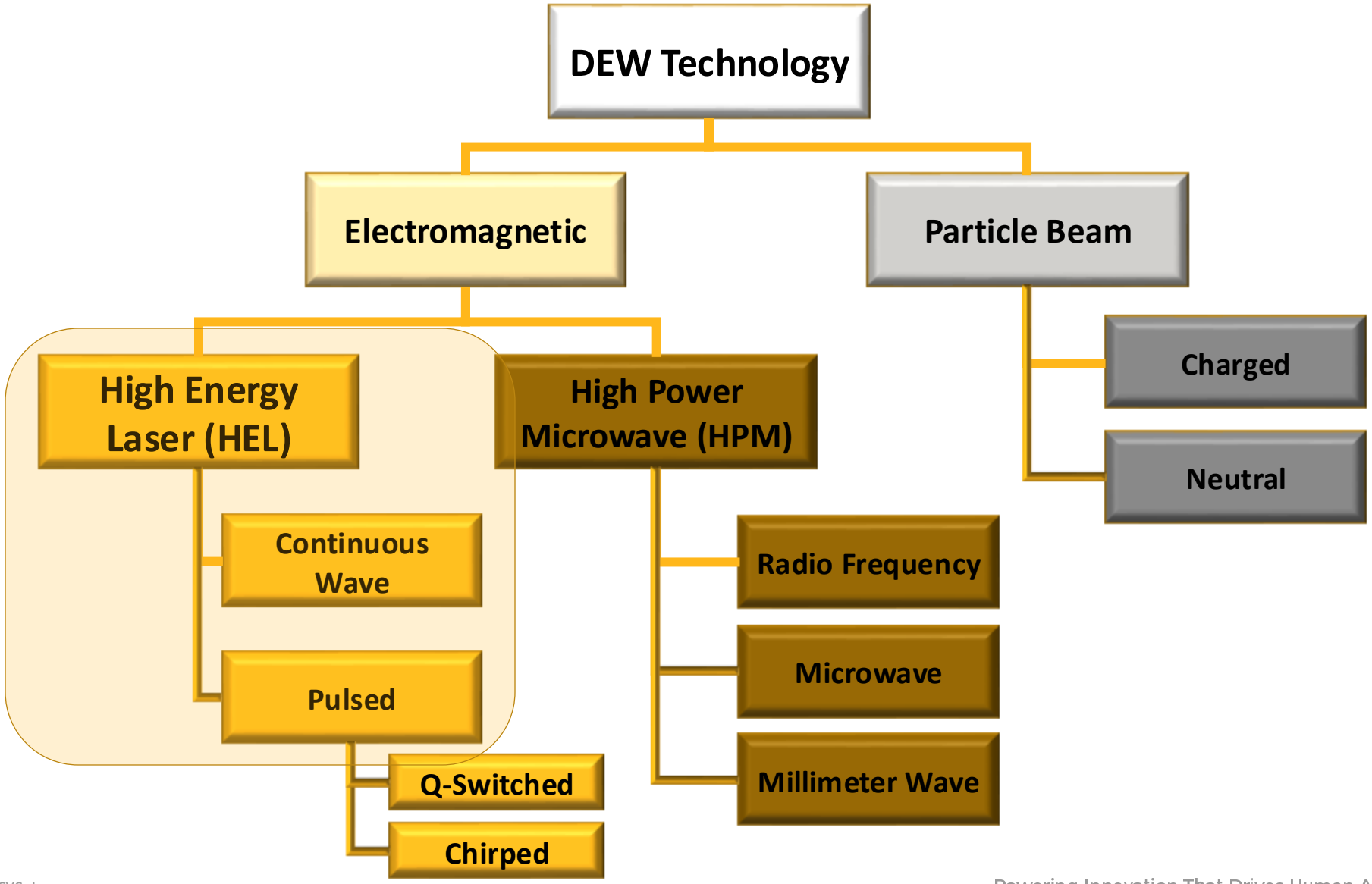
Directed Energy and Optical Effects of Fluids

Advanced Modeling & Simulation (AMS) Seminar Series
NASA Ames Research Center, February 6th, 2025

Steven La Cava

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DEW: Directed Energy Weapons Taxonomy



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DEWS: Advantages, Limitations, Government Viewpoints, & Funding

High Energy Laser Systems	
Advantages	• Fast engagement times, Rapid counter maneuver of missiles, Precision engagements, Graduated responses
Limitations	• Line of sight, Atmospherics (absorption, scattering, & turbulence), Thermal blooming, Saturation attacks

High Power Microwave Systems	
Advantages	• Temporary / system-specific impacts, Broad impacts, Nonlethal applications, Limiting collateral damage
Limitations	• Range constraints, Potential for fratricide, Effectiveness of countermeasures

Government Concerns

- Technological Maturity
- Cost
- Weapons Characteristics
- Mission Utility
- Defense Industrial Base
- Intelligence Requirements
- Coordination within DOD
- Arms Control
- Funding
- Program Effectiveness

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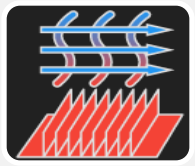
3

Laser Weapons Design and Performance Considerations



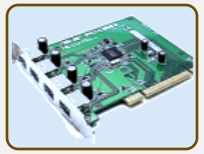






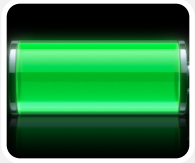
Thermal Management

- Heat removal mechanism
- Heat dissipation devices
- Thermal impact on laser duty cycle



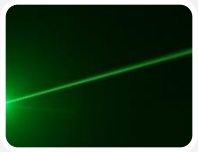
Electronics

- SI, PI, EMI, EMC
- PCB electrical-thermal-mechanical performance and reliability



Power Supply

- Battery, power electronics
- Reactive flow, chemical reaction
- Power capacity ⇔laser duty cycle



Beam Generation, Control, Propagation

- Laser cavity and optical lens system
- Atmospheric & Aero-Optical effects
- Thermal blooming



Antenna and Radar

- Antenna design, co-site analysis
- Target acquisition and tracking
- Radar Cross Section (RCS)



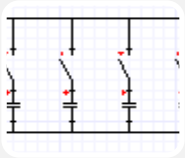
Target Impact

- Target irradiation
- Target heating and degradation



Structure

- Structural stability and integrity
- Random vibration & shock scenarios
- Weight and size reduction



Systems Integration

- Integrated subsystems
- Integrated platform energy demands
- Integrated embedded SW, AI

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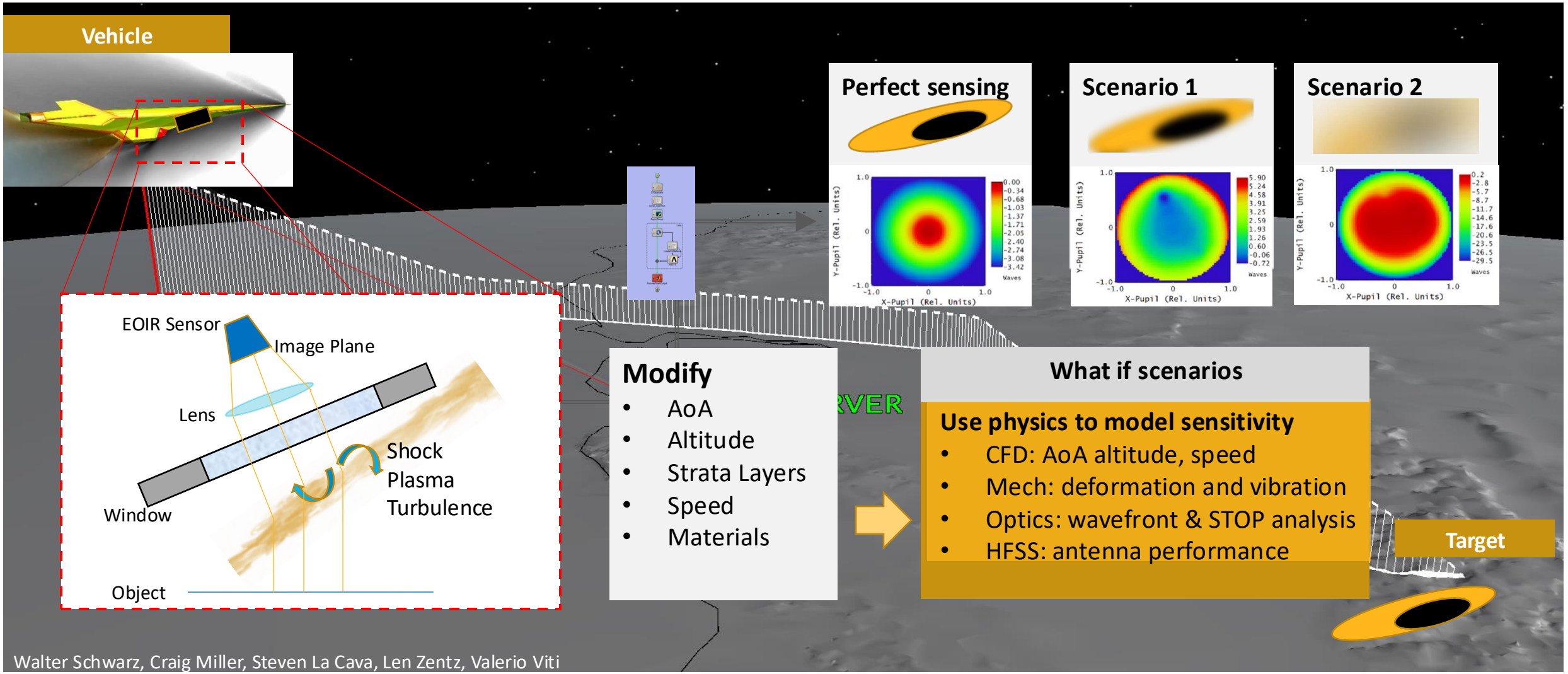


Problem Statement & Approach

EOIR / Trajectory / Species / Turbulence / Thermal

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Sensitivity of Optical Sensing Under Different Conditions

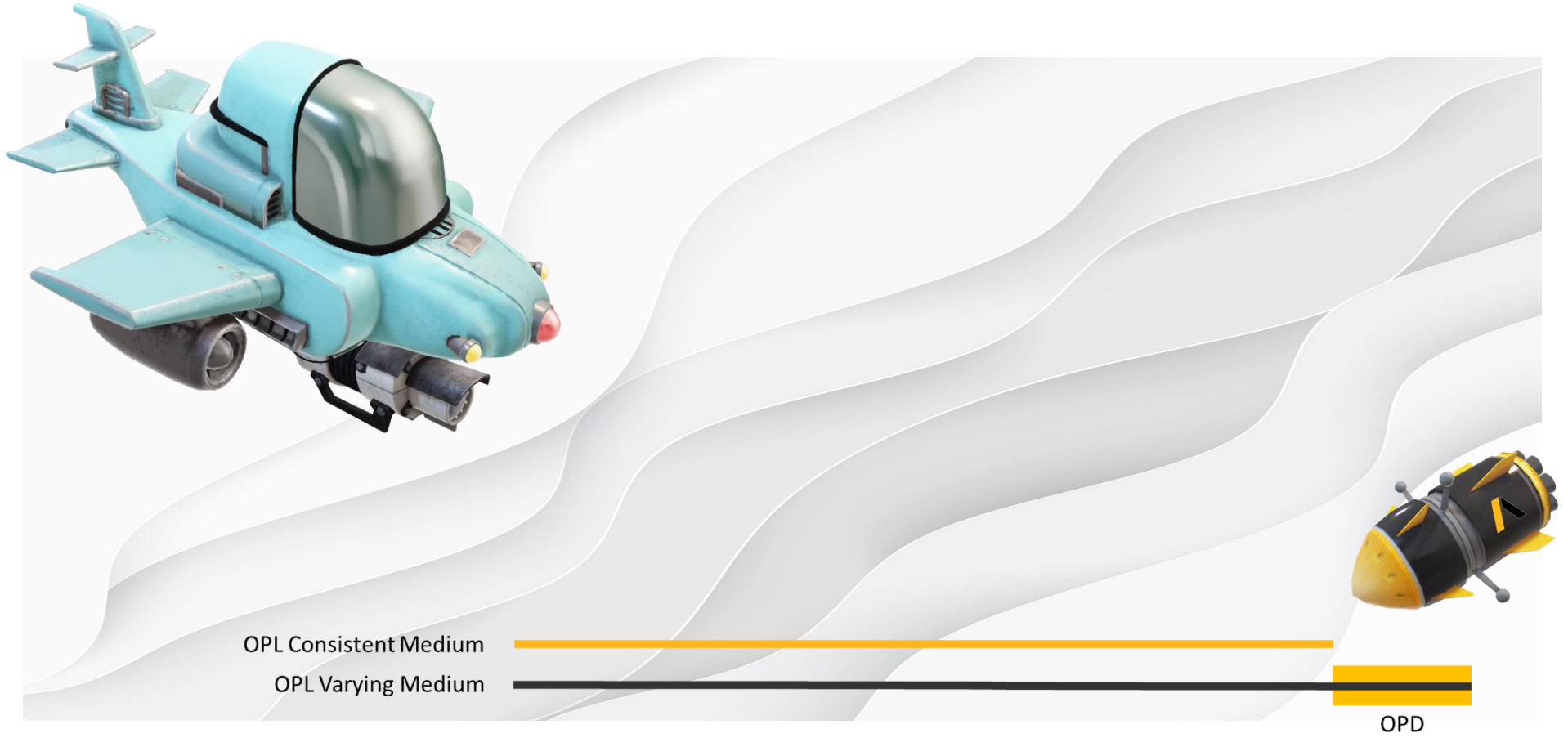


Walter Schwarz, Craig Miller, Steven La Cava, Len Zentz, Valerio Viti

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For example: Aero-Optics

Aircraft-induced flow disturbances that affect an optical system’s performance.



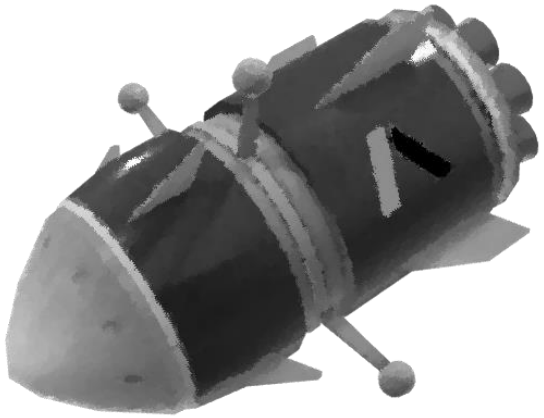
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Aero-Optics + STOP effects explained

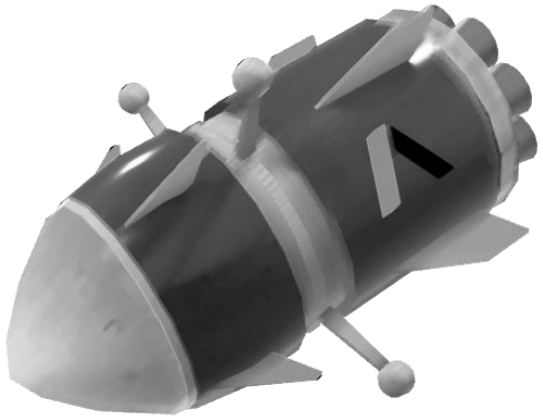
Not actual simulation results



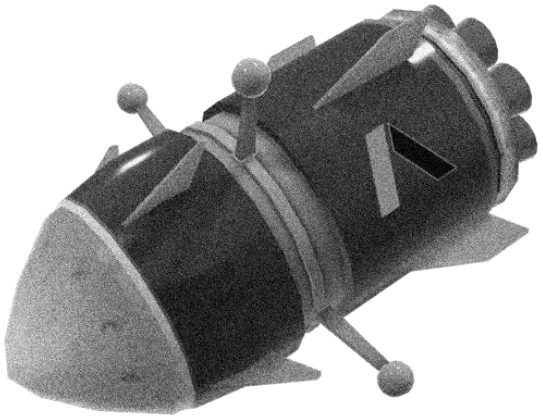
Nominal



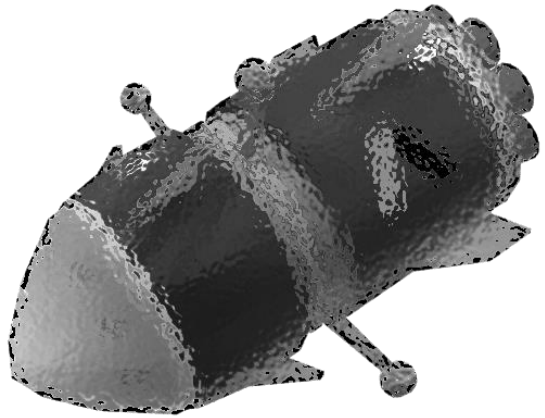
Structural



Thermal



Fluids

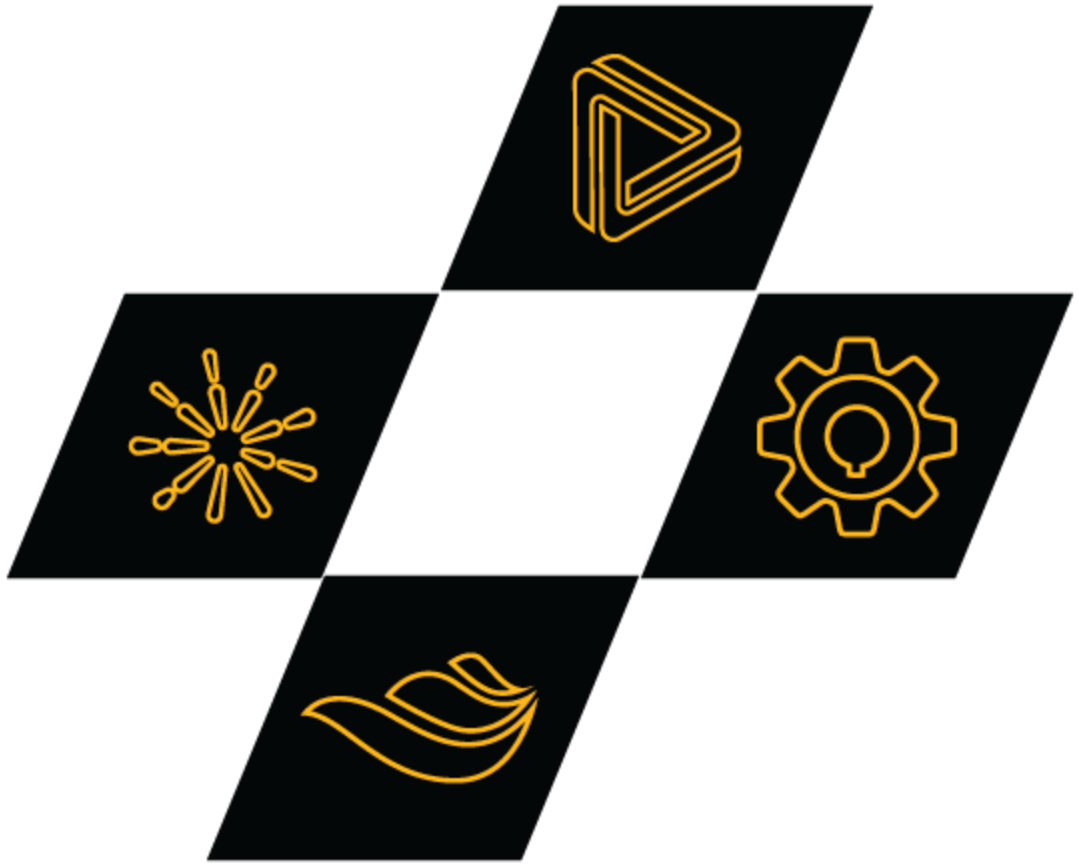


Structural + Thermal + Fluids

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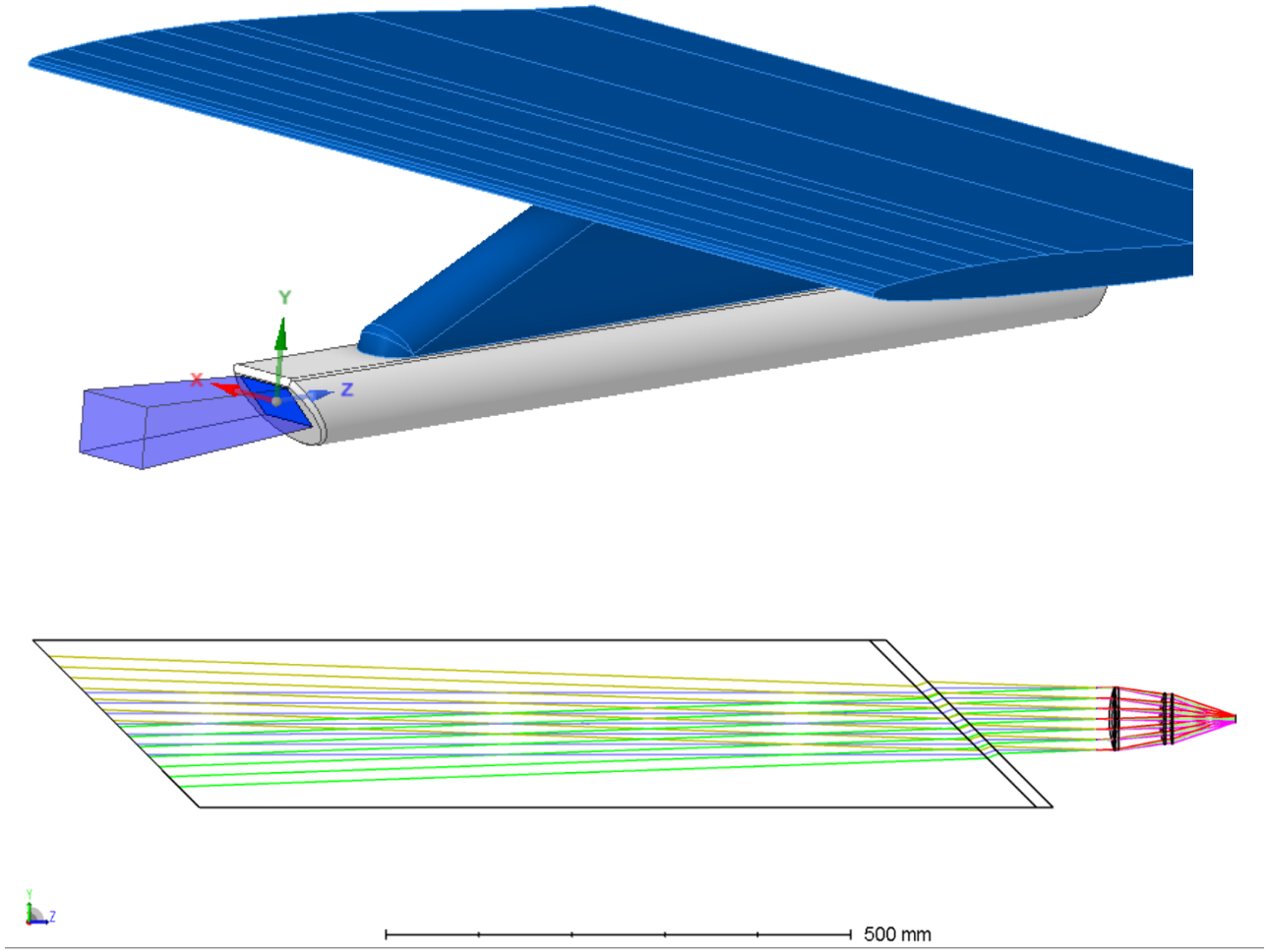
Multiphysics STOP -> SOFT Analysis Workflow Components

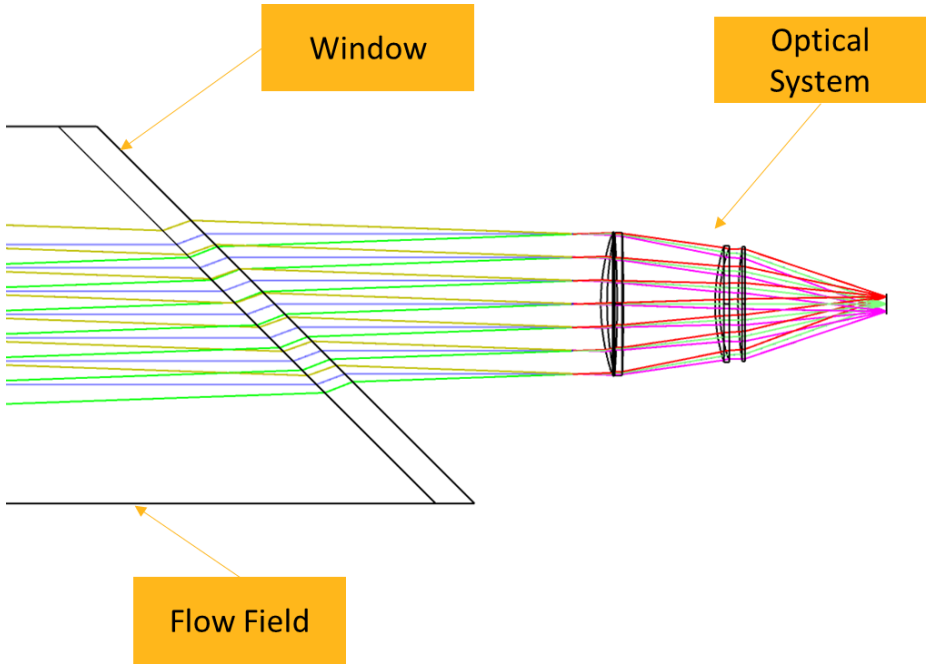
- Mission Driven Physics
  - Trajectory & Solar Load
  - Strata Layers & Species
- Computational Fluid Dynamics (CFD)
  - Flow field boundary & Compression
  - Turbulent Flow & Shockwaves
  - Separation & Ionization
- Finite Element Analysis (FEA)
  - Mechanical Deformations
  - Thermal Lensing & Index of Refraction
- Optics
  - Design, tolerancing, and analysis.
  - STOP: **S**tructural, **T**hermal, **O**ptical **P**erformance
  - SOFT: **S**tructural, **O**ptical, **F**luid, **T**hermal



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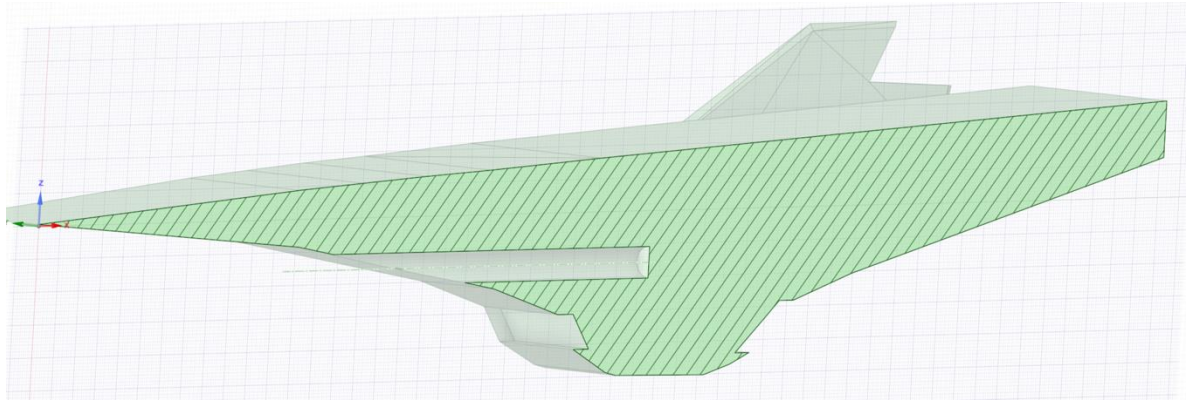
Example: Electro-Optic Infrared System (EOIR)



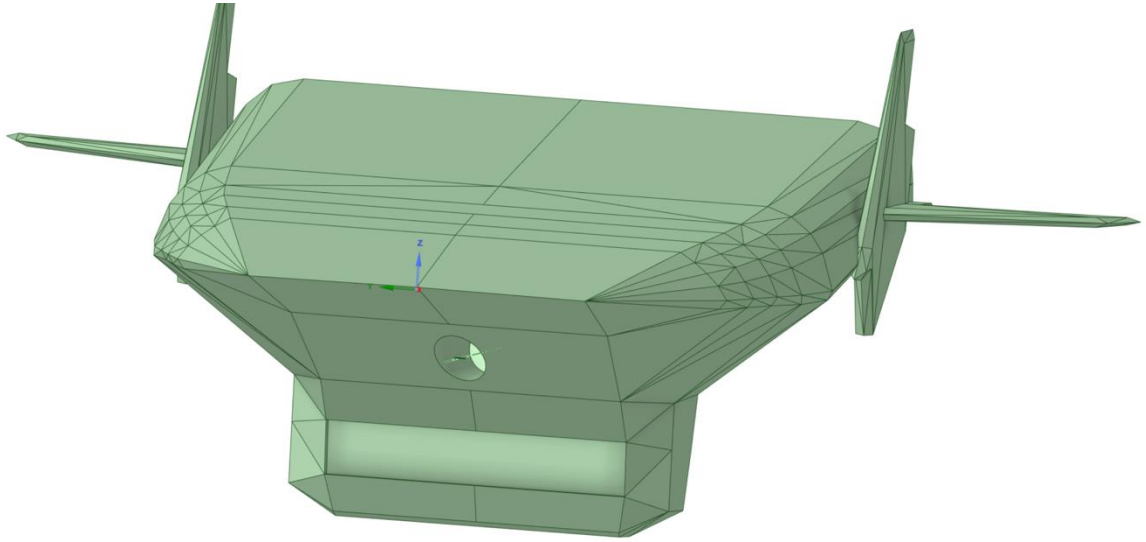


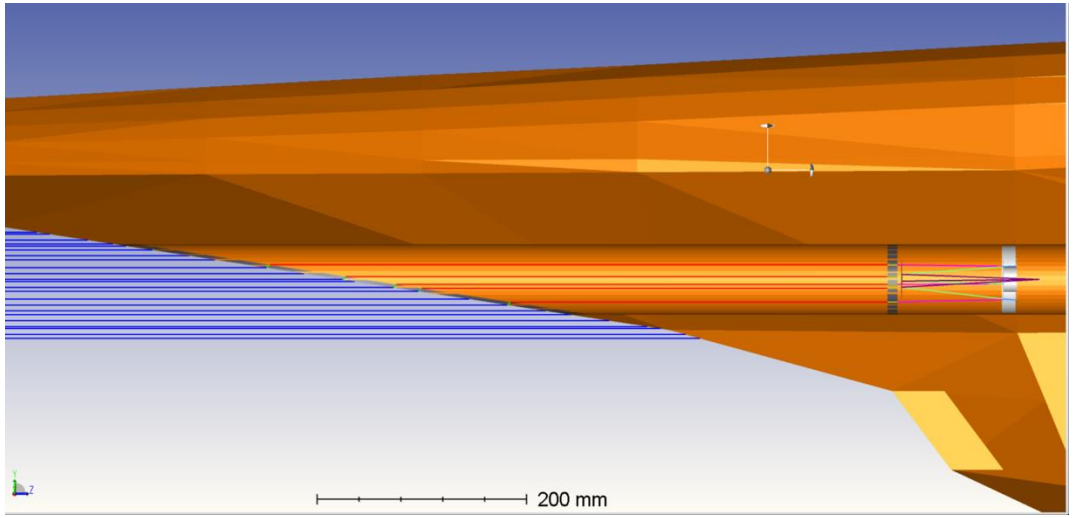
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Optical & Opto-Mechanical Design









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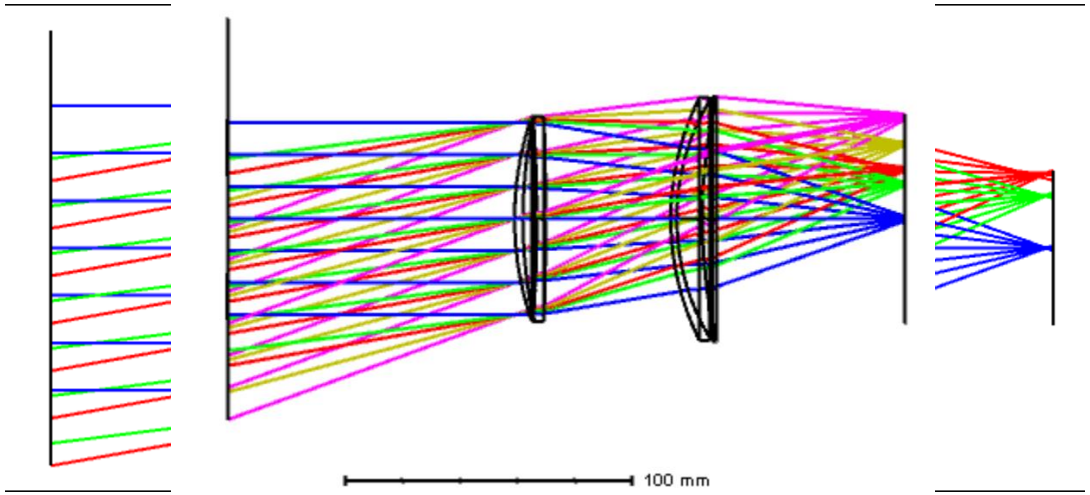
Optical & Opto-Mechanical

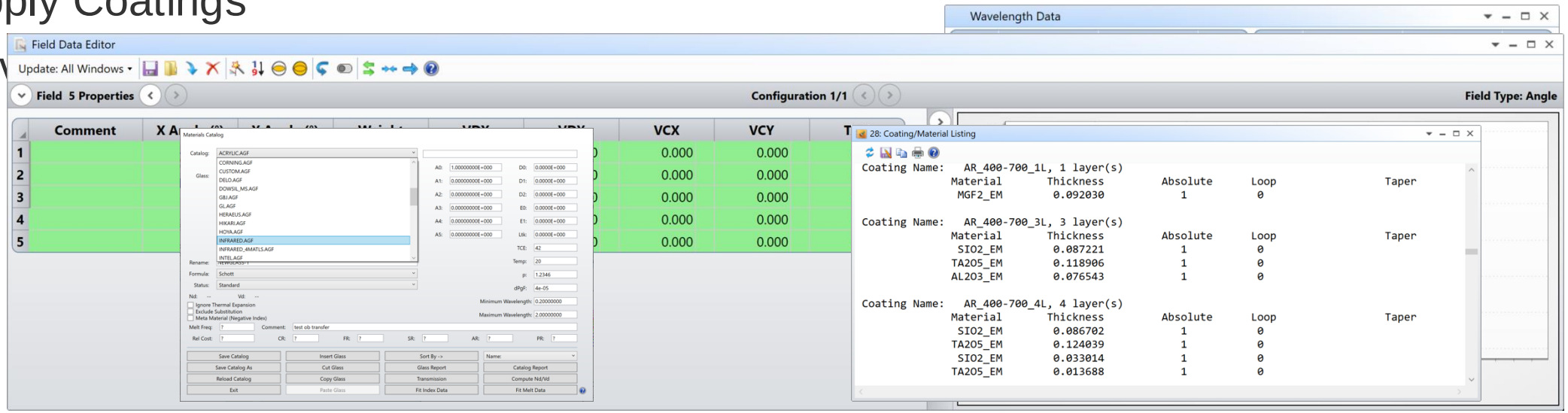
Nominal Design / Benchmarking / Optimization / Tolerancing

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Nominal Optical Design

- Design the nominal system
  - Wavelengths
  - Specify Fields
  - Apertures and more
- Libraries
  - Select materials
  - Apply Coatings
  - Lev

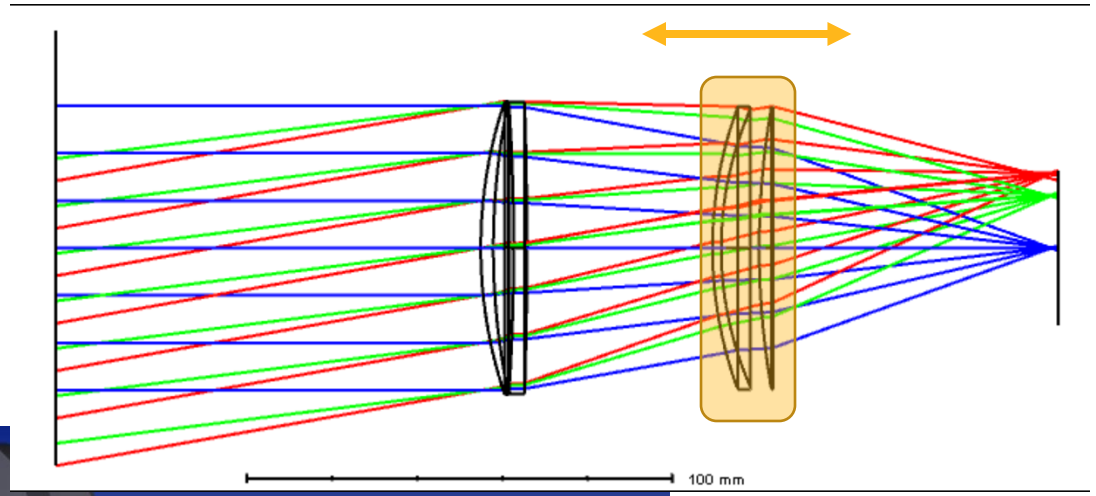


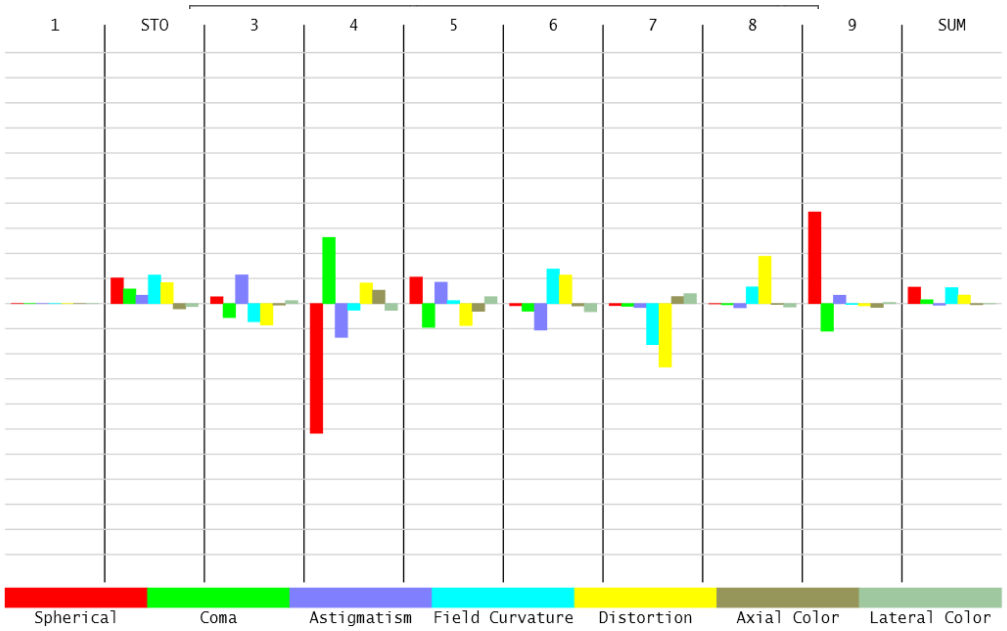


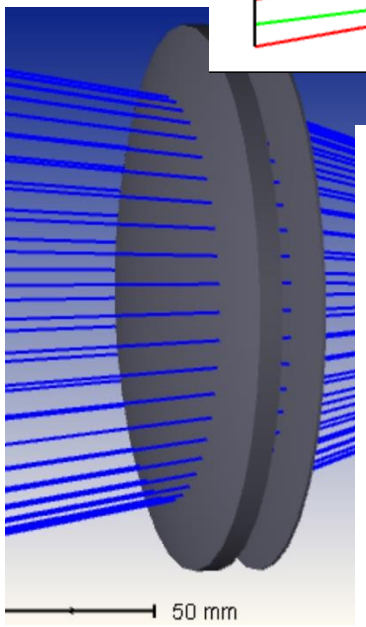
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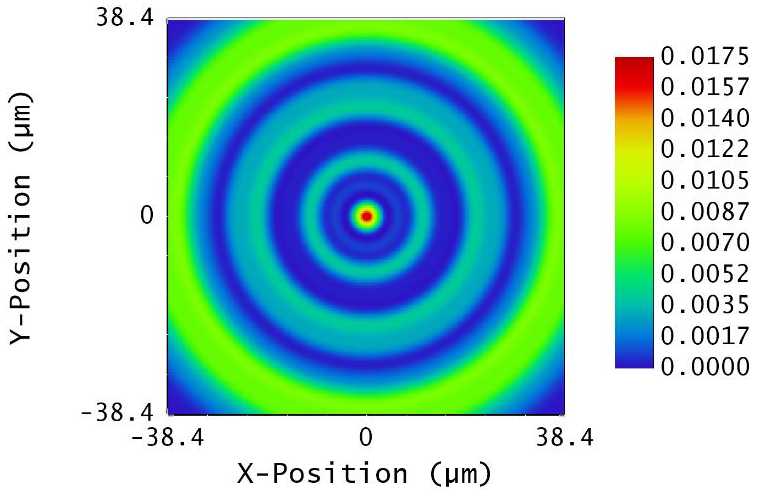
Nominal Optical Analysis

- Optimize and Tolerance the system
  - Optimize around any metric
  - Specify compensators for tolerancing
  - Glass Substitution Catalog
- Export files for opto-mechanical use





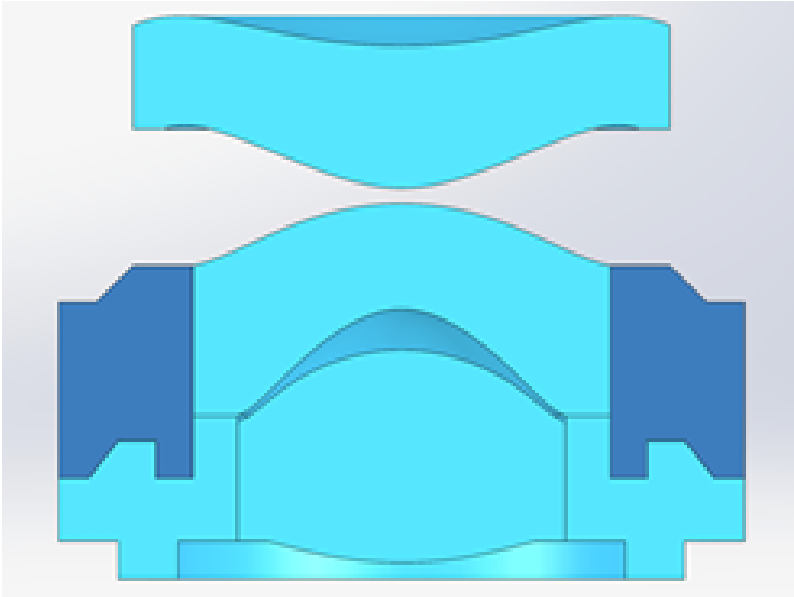




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Optomechanical Design

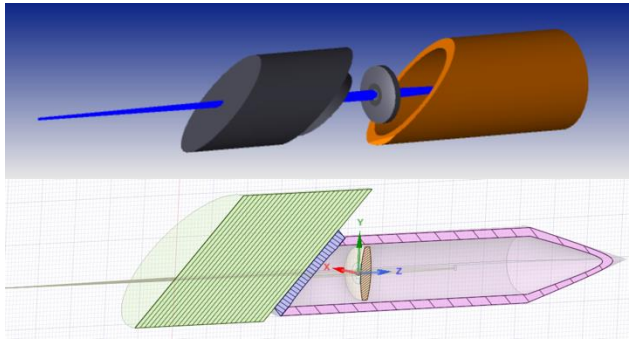
- Seamlessly transition optical design specification to CAD environment, including:
  - Lens geometry
  - Material definitions
  - Light sources
  - Sensor positions
- Incorporate or design mounting structures
  - Mechanical housings
  - Complex lens edges
- Assign materials and surface properties to all opto-mechanics including CAD parts
  - Important to consider factors such as CTE, material weight, & structural load
  - Scattering and Absorption
- Consider impact of both optical and mechanical components while evaluating optical performance metrics

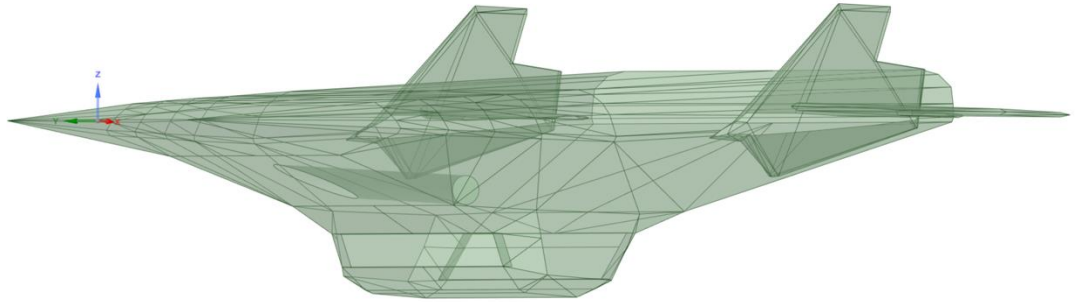


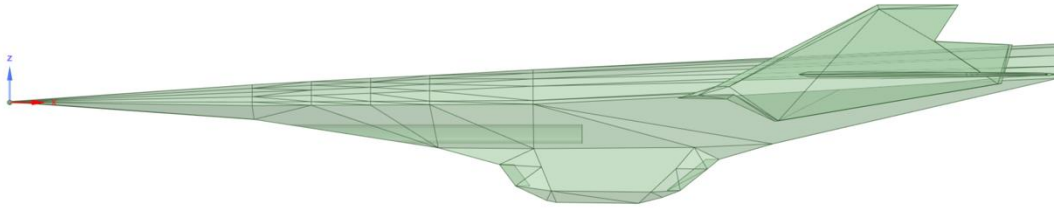
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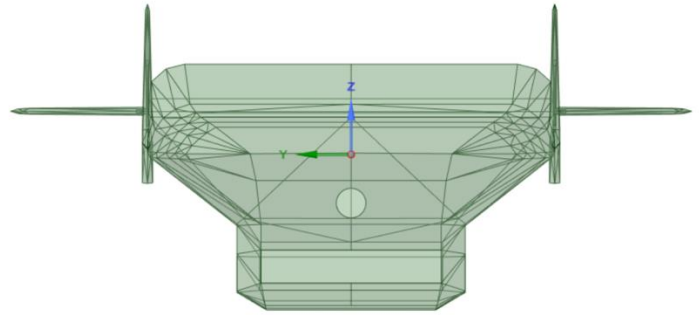
Opto-Mechanical

- While Boolean parts can be created natively in Zemax OpticStudio, CAD tools are better suited for this type of work.
- Consider using Ansys Discovery or Space Claim for to modify the CAD model.
- These tools also have the benefit of allowing defeaturing for use with FEA and CFD workflows.





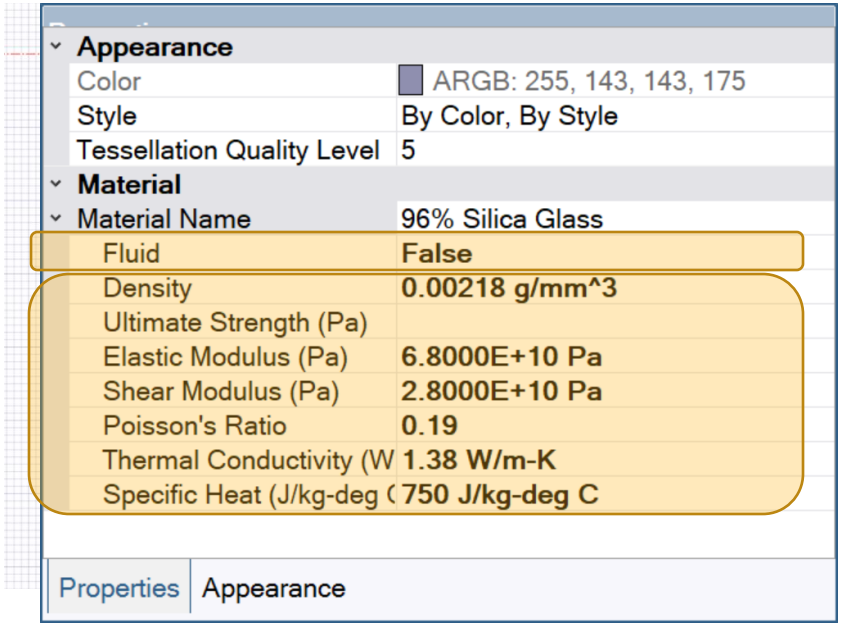


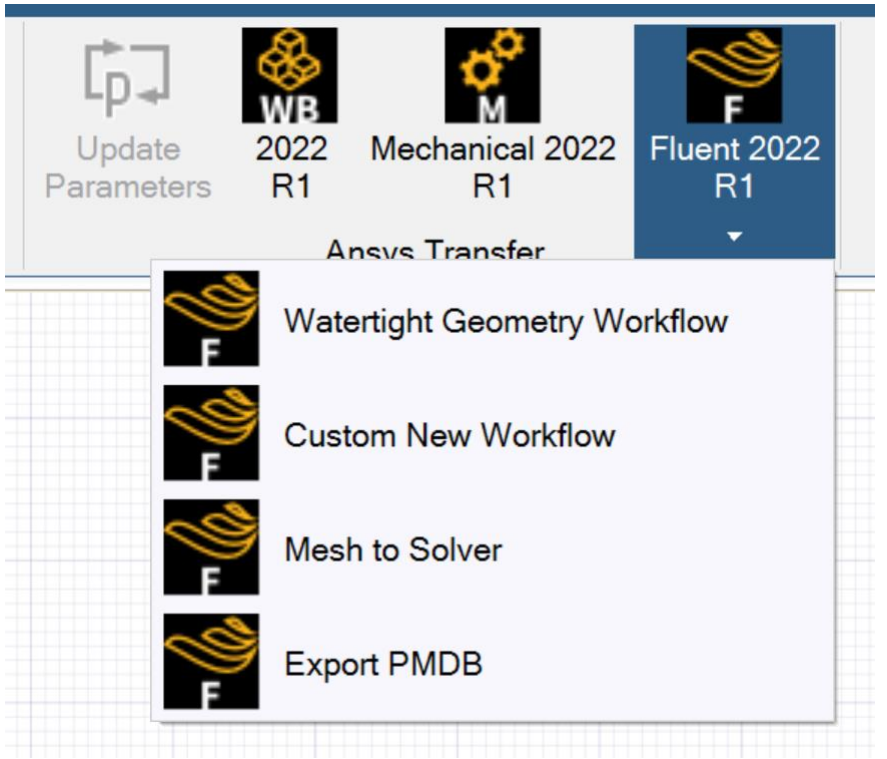


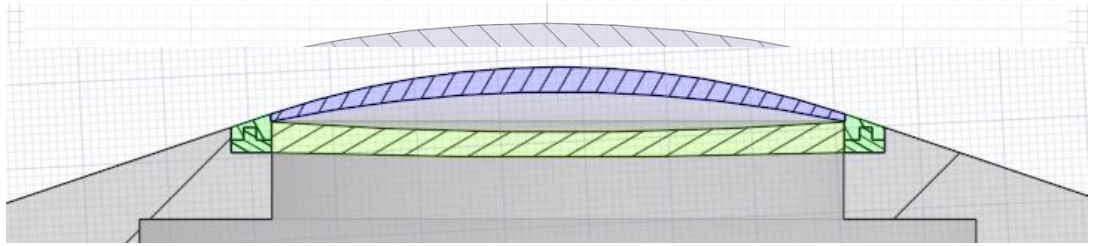
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Opto-Mech to CFD

- Optomechanical System
- Create step mounts on lenses
- Create mounts for larger mechanical system
- Combine mechanical components with optical elements
- Apply material properties to CAD parts
- Create Fluid Regions for use in Fluent
- Carry properties to Mechanical and Fluent
- Launch other Ansys Programs with starting data







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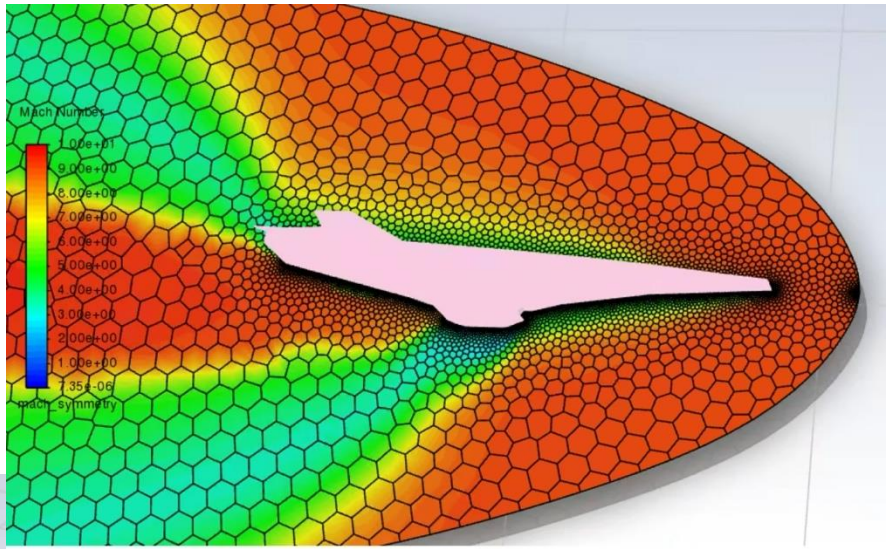
STOP Analysis

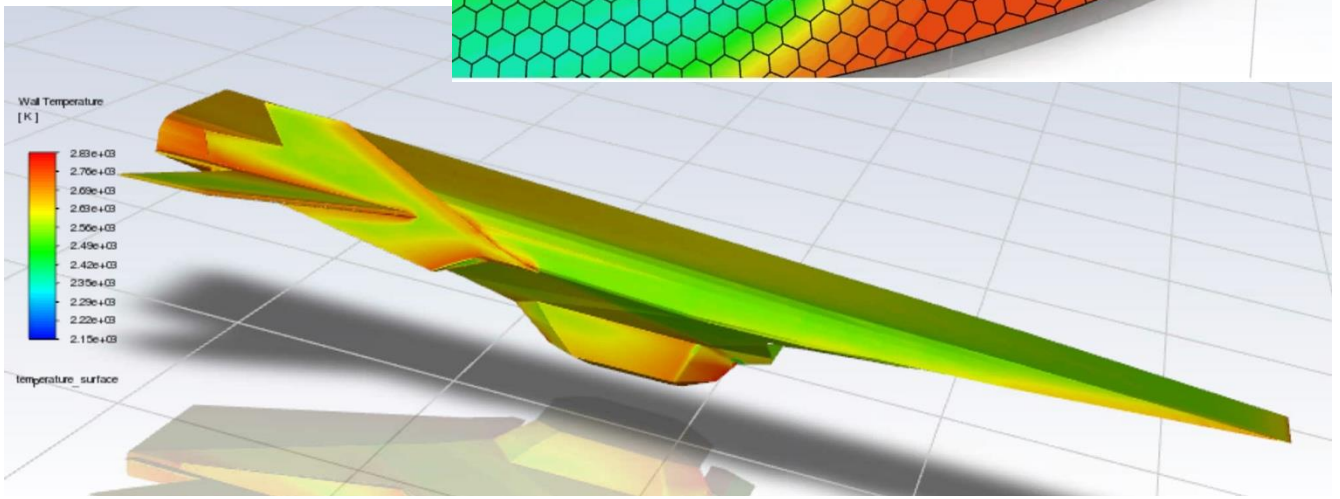
Structural / **T**hermal / **O**ptical / **P**erformance

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Initial Conditions

- CFD (Computational Fluid Dynamics are necessary to create the initial conditions used for FEA (Finite Element Analysis.
- The velocity, angle of attack, viscosity, and other factors of the flow field all play a large role in the temperatures and pressures the vehicle will undergo.
- It is worth noting, that while Ansys has streamlined the process with our tools, this workflow is software agnostic, it will work with COTS, GOTS and even Homebrew code.

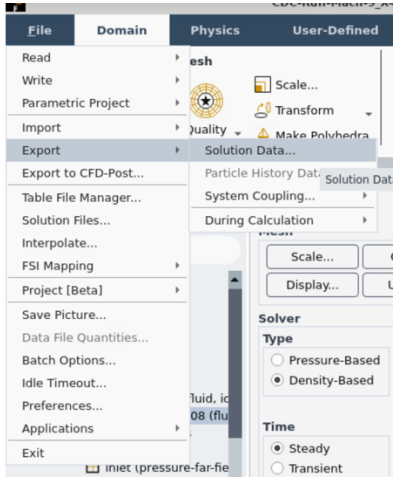


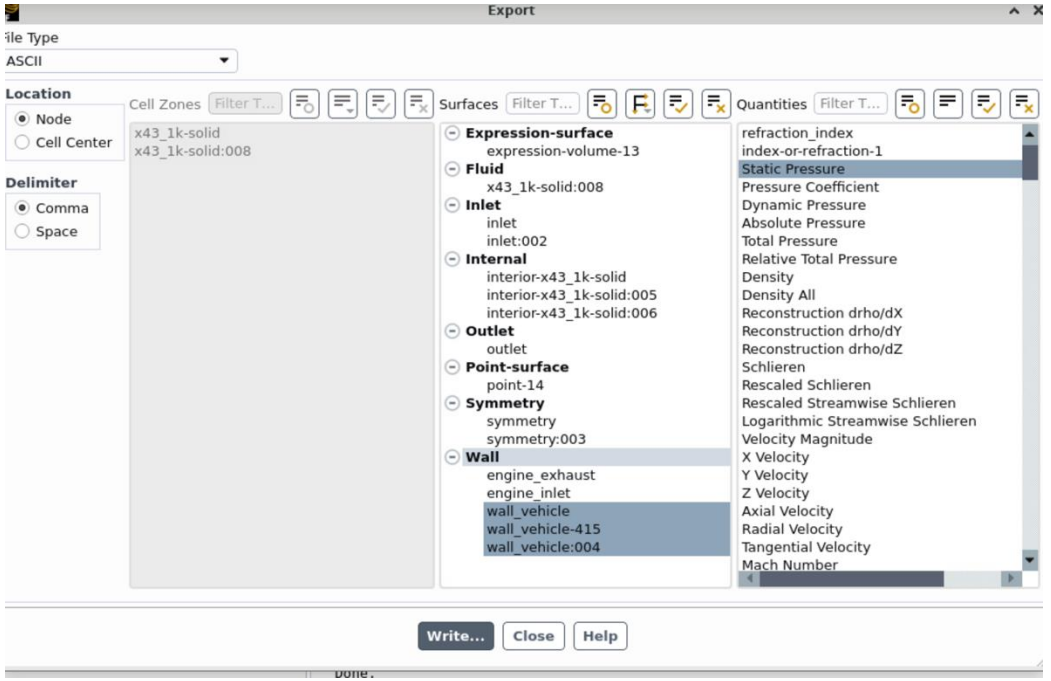


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Exporting Mechanical Data from Fluent

- There are number of items that may be needed when exporting Fluent data for Mechanical, depending on the analysis to be performed.
- Exports can be made as either Nodes or Cell Centers, Nodes are the vertices points of the mesh and Cell Centers are a point value in the center of the three dimensional cell.
- For this example the following are needed.
  - Static Pressure
  - Static Temperature
  - Surface Heat Transfer Coefficient
  - Wall Adjacent Heat Transfer Coefficient

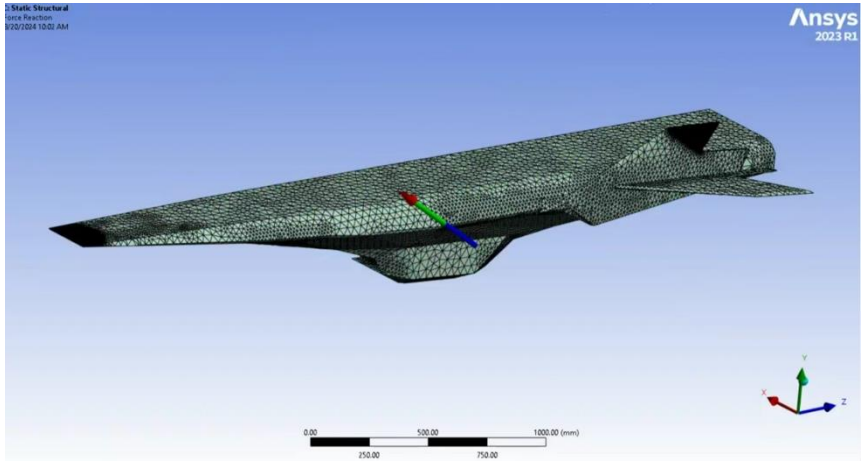


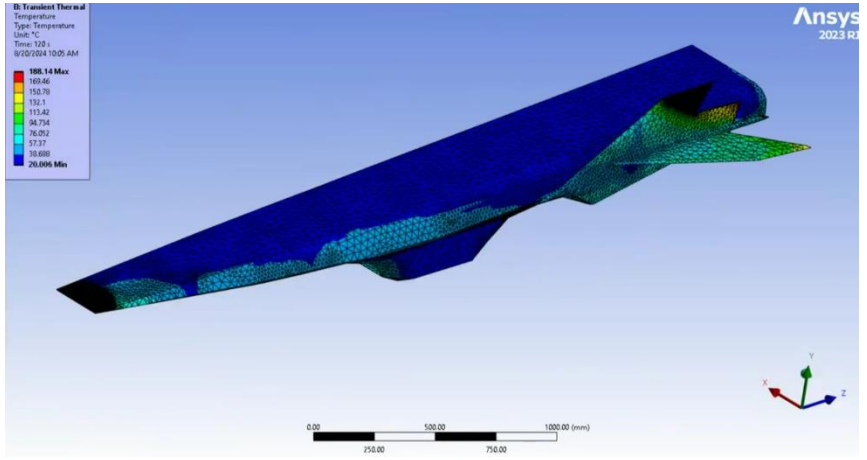


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Mechanical Analysis

- Import the initial conditions from Fluent
- Conduct a Mechanical Analysis compare many metrics and variables

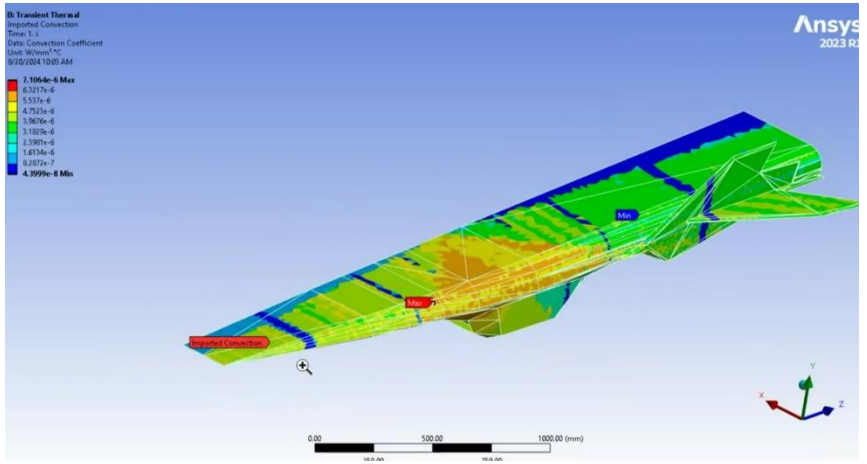


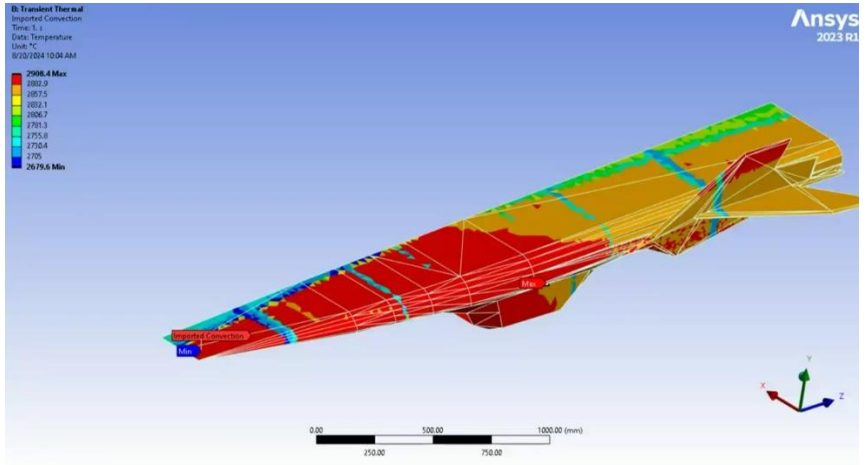


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Mechanical Analysis

- Analyze the transient system
- Identify times steps of interest for optical analysis



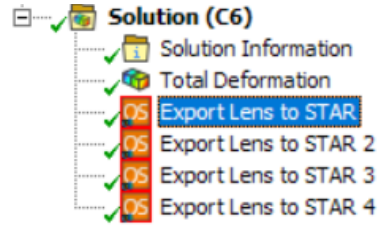


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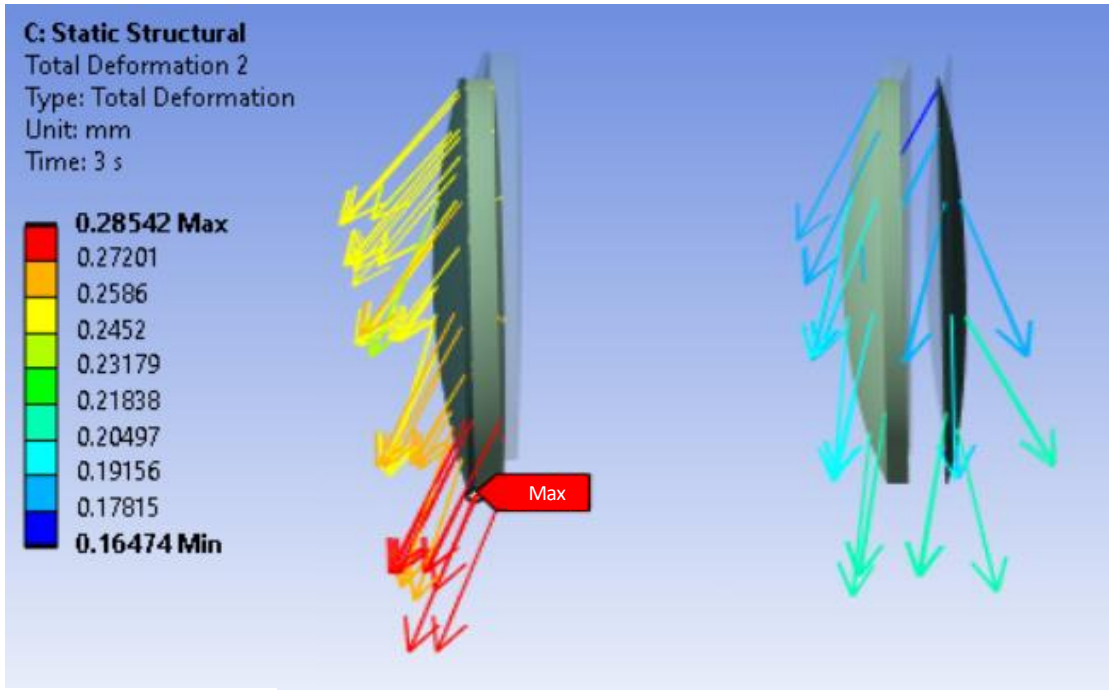
Transient Thermal & Static Structural

- Support is “inertial relief”
  - For quasi-static, artificial acceleration at CG that counterbalances applied loads to simulate a minimally constrained structure
- Lens surface distortions and volumetric temperatures are exported

Exporting to OpticStudio



Displacement Results



Details of "Export Lens to STAR"

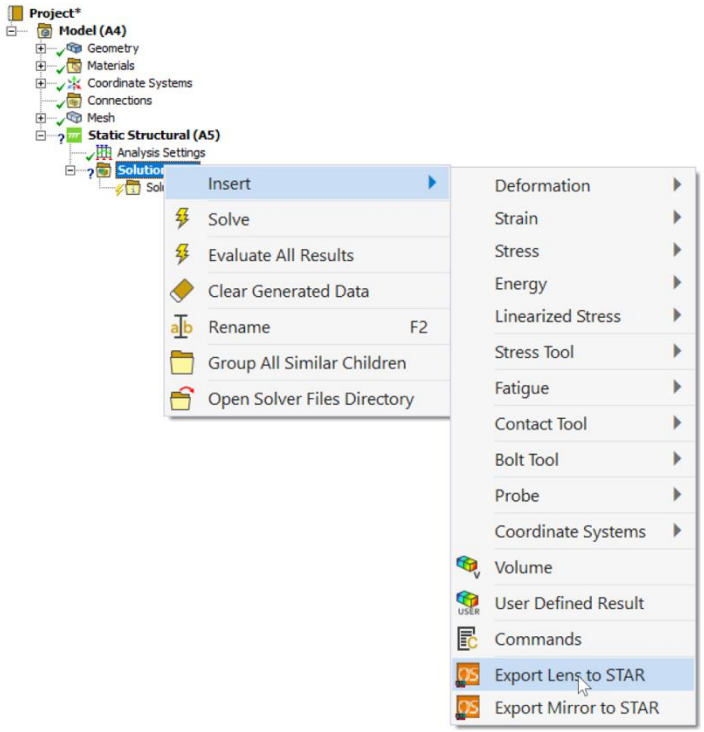
Volume	
Scoping Method	Named Selection
Named Selection	Lens_1
Front-Surface	
Scoping Method	Named Selection
Named Selection	Lens_1_Front
Back-Surface	
Scoping Method	Named Selection
Named Selection	Lens_1_Back
Definition	
Front Surface Zemax ID	1
Front Coordinate System	OpticStudio CS
Back Surface Zemax ID	2
Back Coordinate System	OpticStudio CS
Exported Timesteps	All Timesteps
By	Time
Display Time	Last
Identifier	Lens_1St

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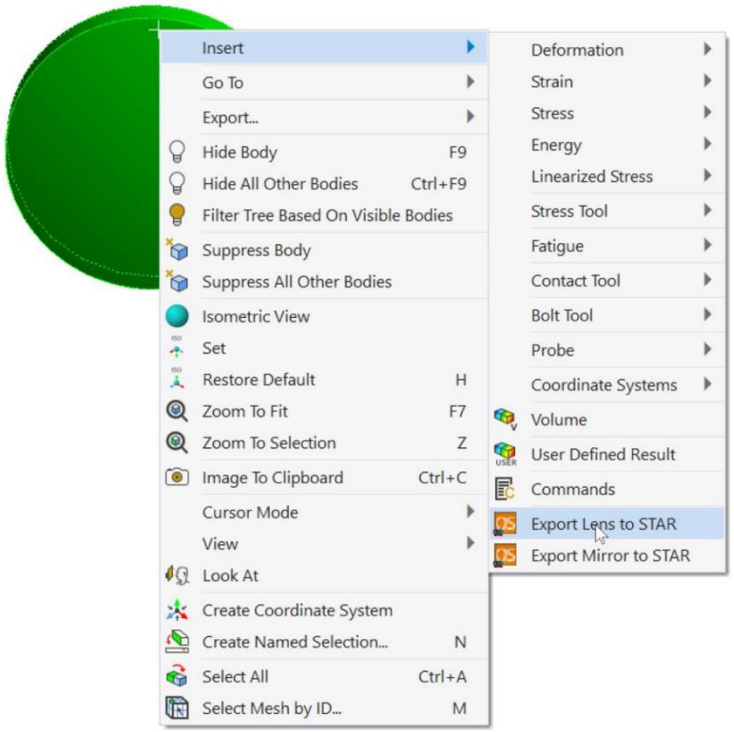
Mechanical: Export with ACT Extension

- The ACT script for Ansys Mechanical to export FEA data to STAR can be accessed in other ways too
- This can be initiated from the part tree, or directly from the part

Access from the tree



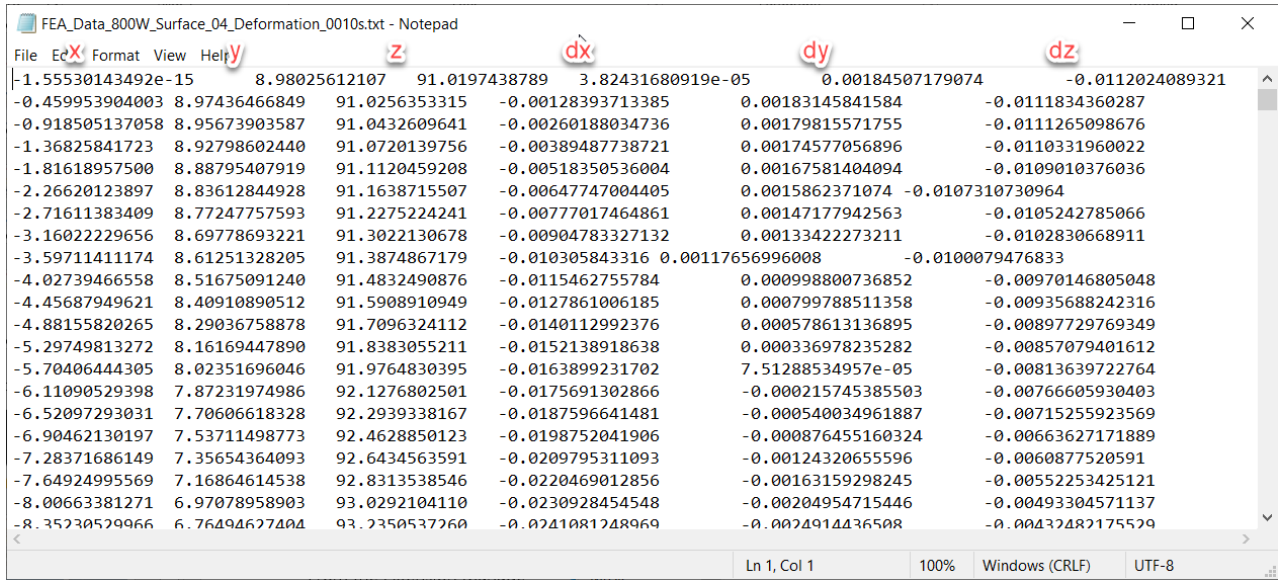
Access from the part

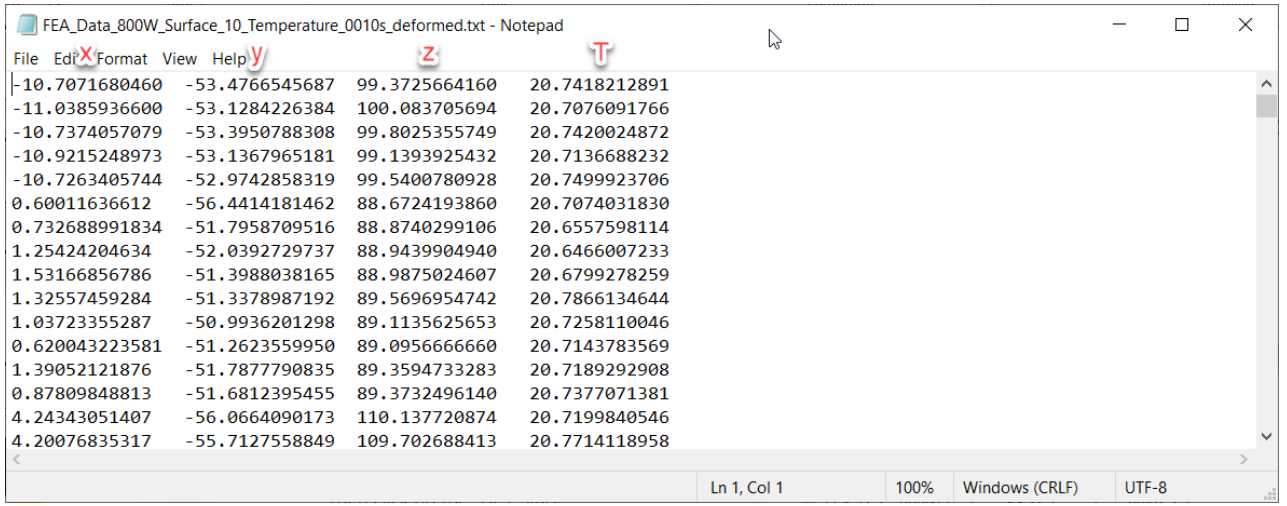


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Formatting

- The text (.txt) files need to follow the format on the previous slide, with no headers.
- The images to the right are an example of the formated text file have the columns designated with their respective term in red.

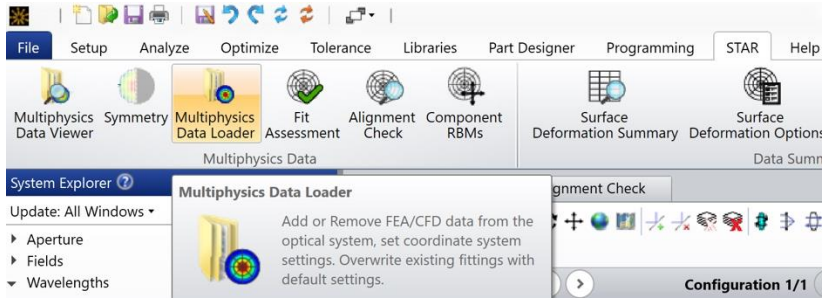


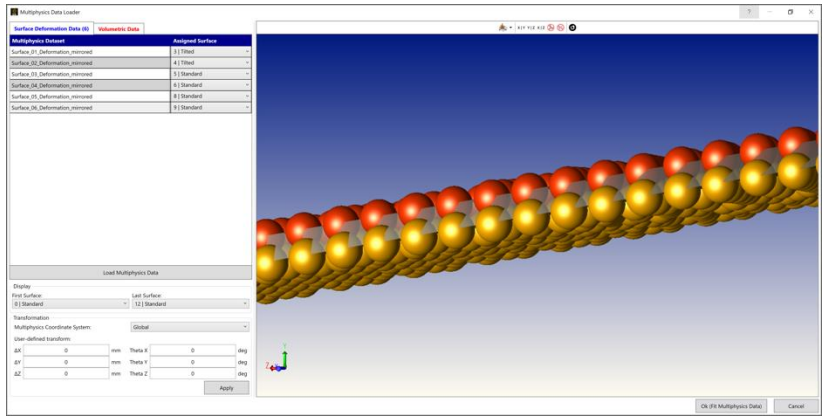


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Load Data

- From the STAR tab select Multiphysics Data Loader
- Next select the button “Load Multiphysics Data”
  - Note the Multiphysics data loader supports many data types, including surface deformations, volumetric thermal data sets, direct index of refraction data from fluid or other sources, even measured data could be imported provided it is the correct type and format.
- Next the coordinate system is very important and typical source of error, as many mechanical file propagate in the X-Direction and many optical system propagate in the Z-Direction.

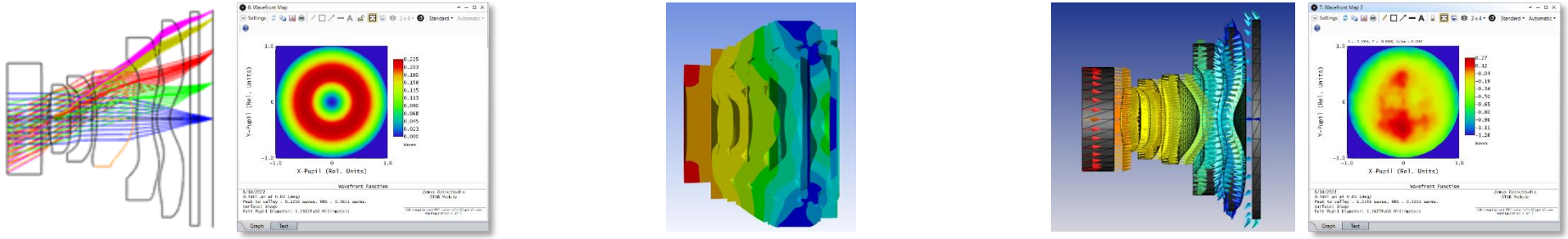




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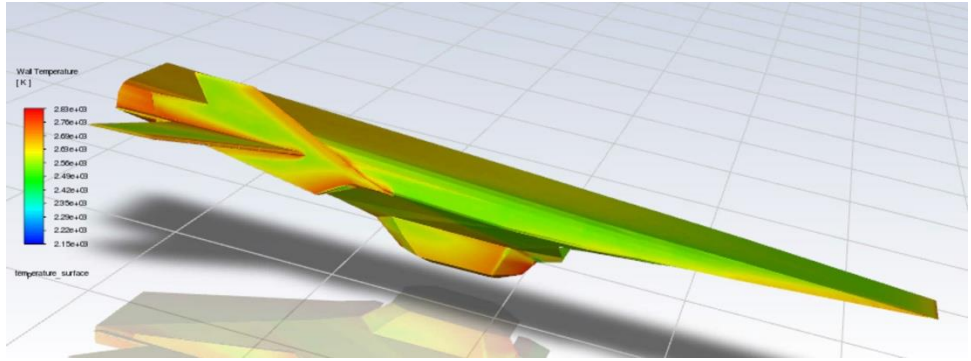
Structural Thermal Optical Performance

- Perform nominal optical system design in OpticStudio
- Send to CAD to incorporate optomechanical system design
- Send to CFD to determine flow fields
- Send to FEA to apply structural and thermal loads (surface deformation & thermal index variation)
- Import deformed system and flow field index profile to OpticStudio to analyze optical performance.

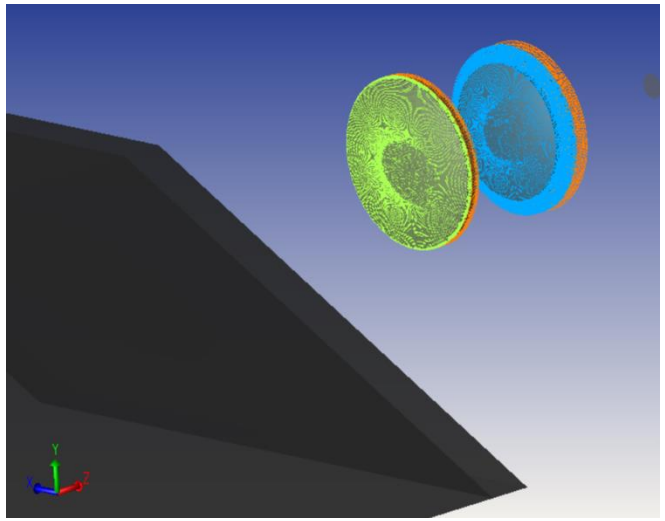


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STOP Analysis



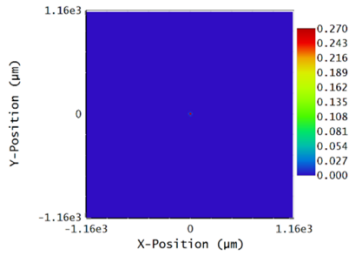
Nominal

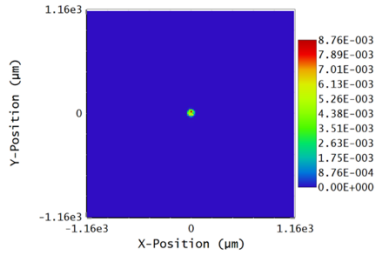


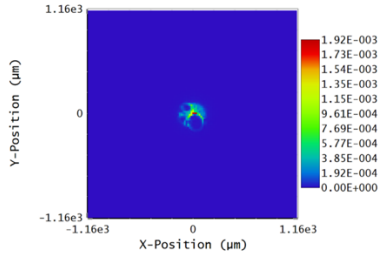
Structural

Thermal

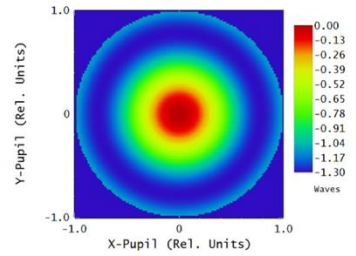
PSF
Point Spread Function

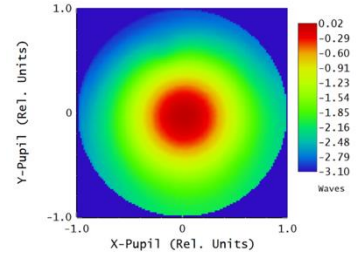


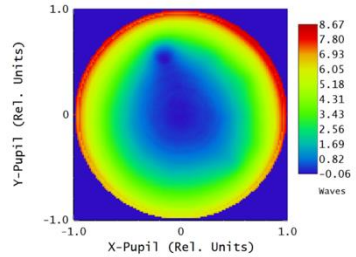




Wavefront
Map



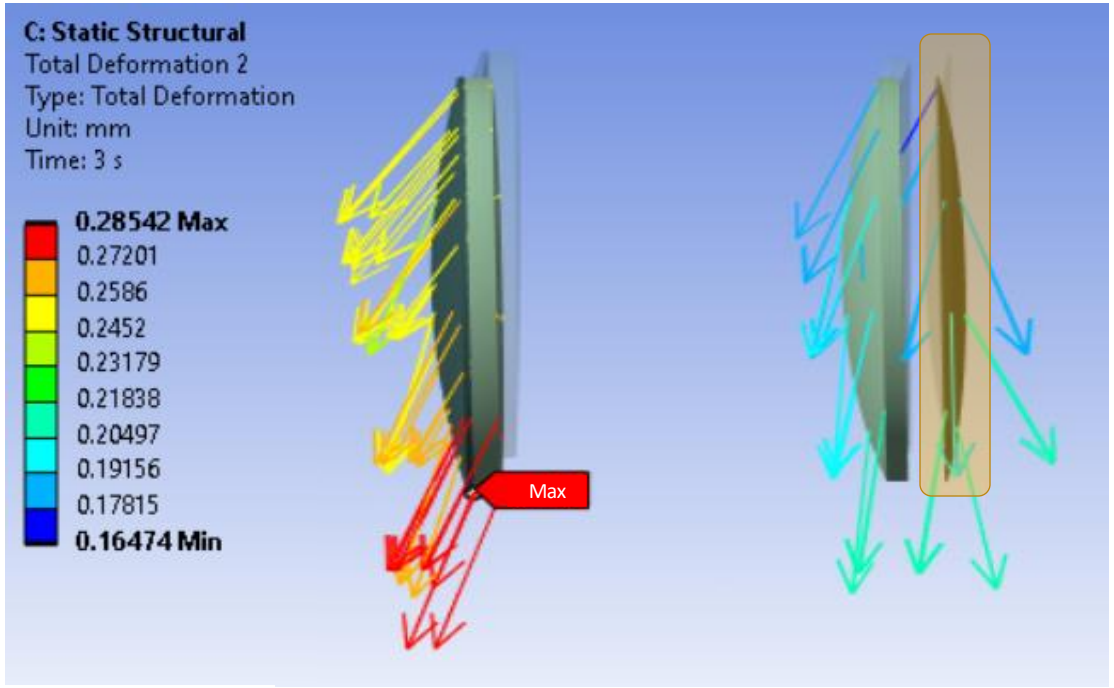


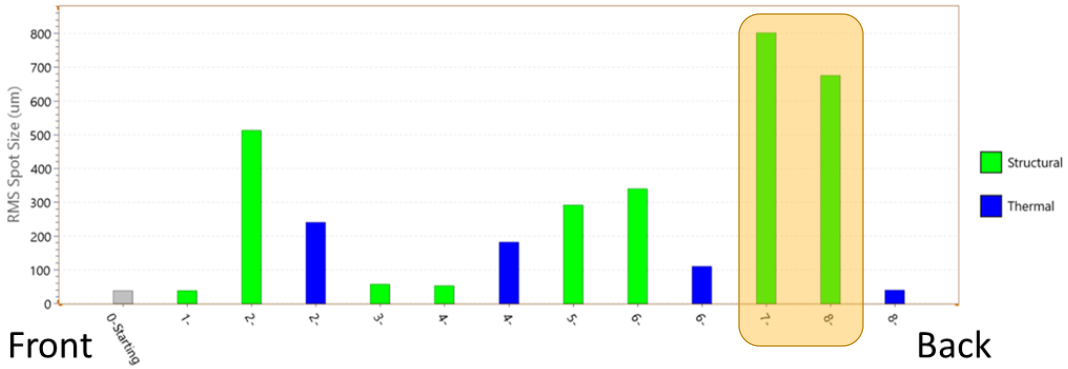


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Moving Simulation to the Left in the Process Saves Money!

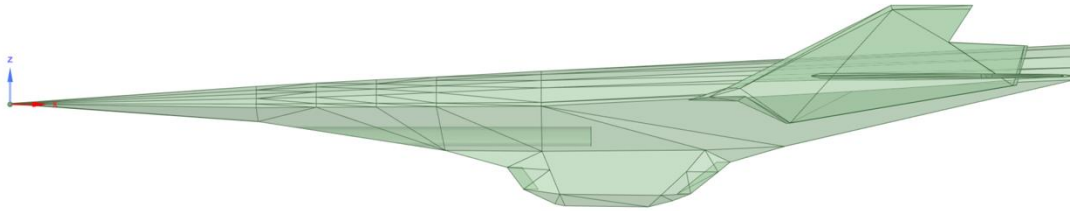
- Catching unexpected behavior and potential errors before prototyping, build and testing saves a lot of time and money.
- Allows greater flexibility in design changes and options.

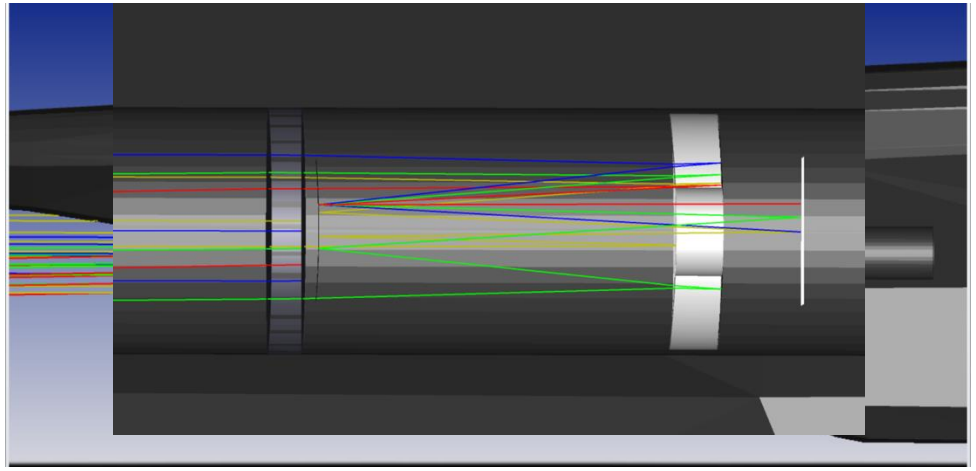


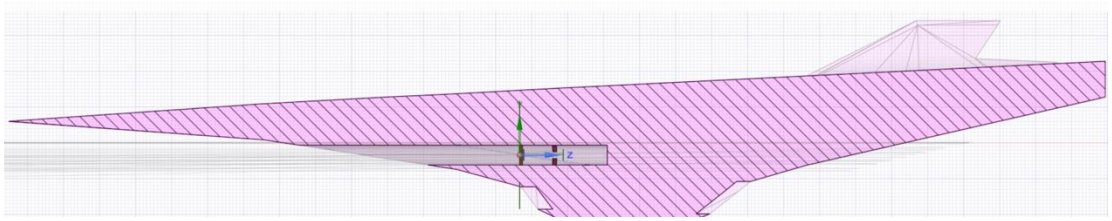


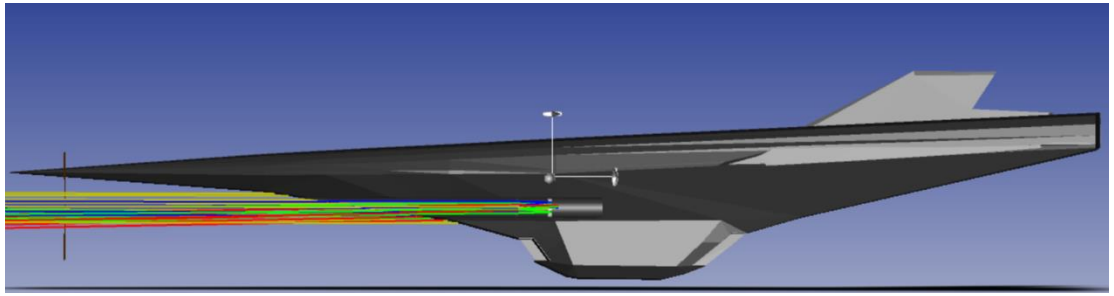
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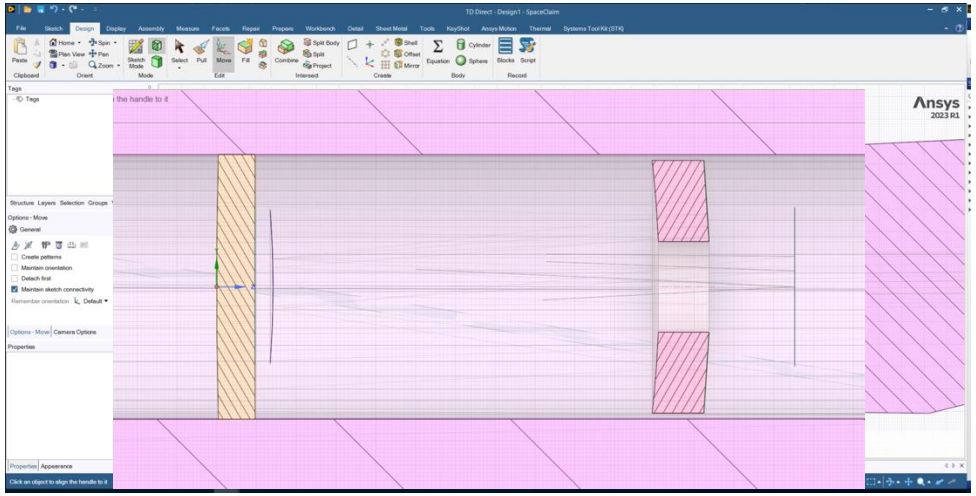
Opto-Mechanical Iterations (Changes to Design)





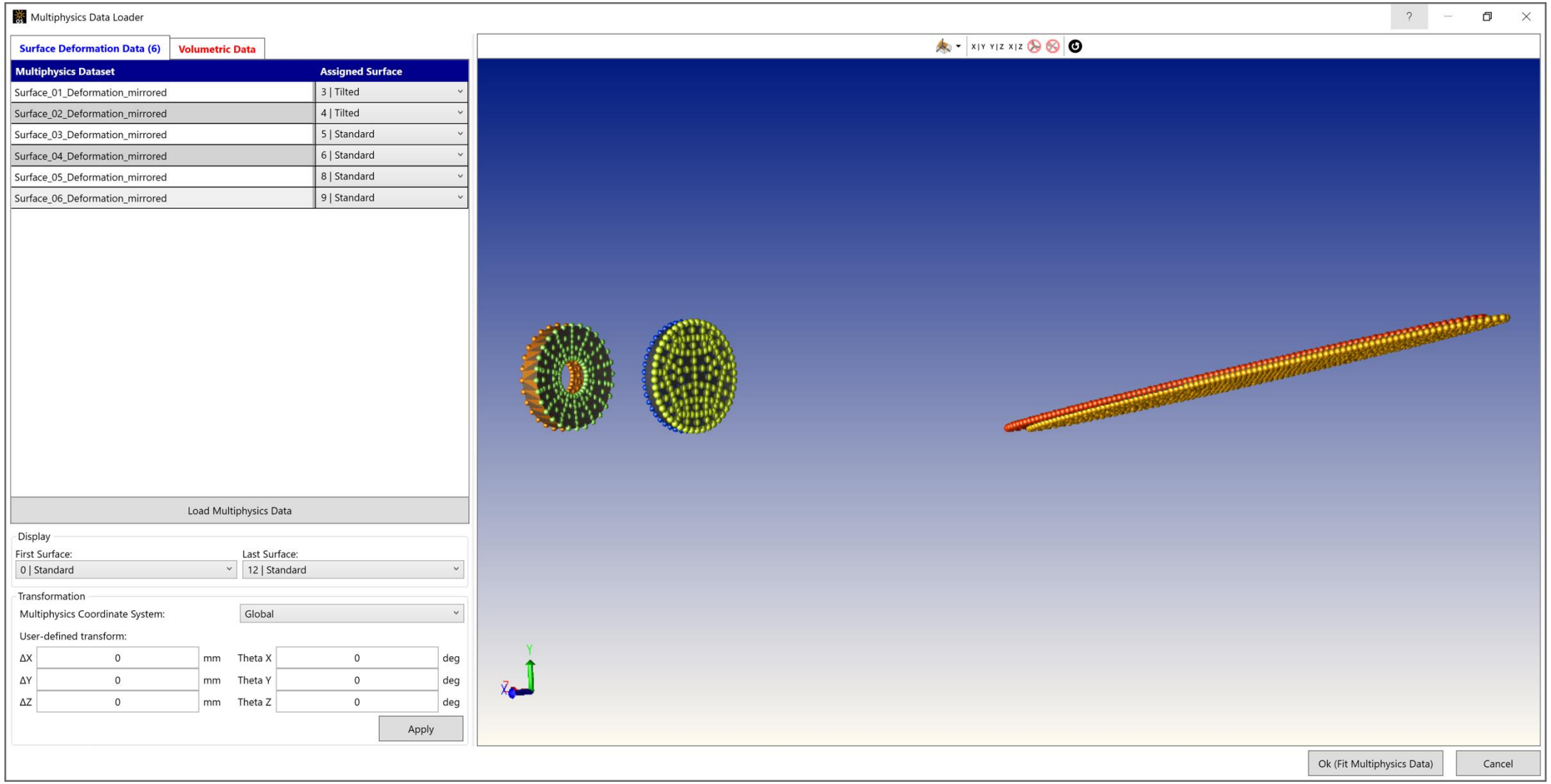






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Export and Import the New Iteration



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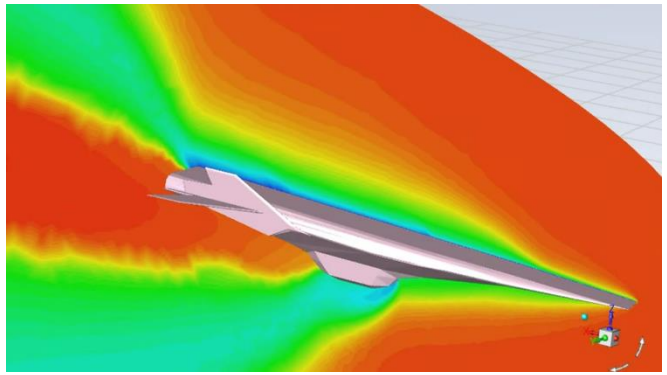
Aero-Optical & Fluid Analysis

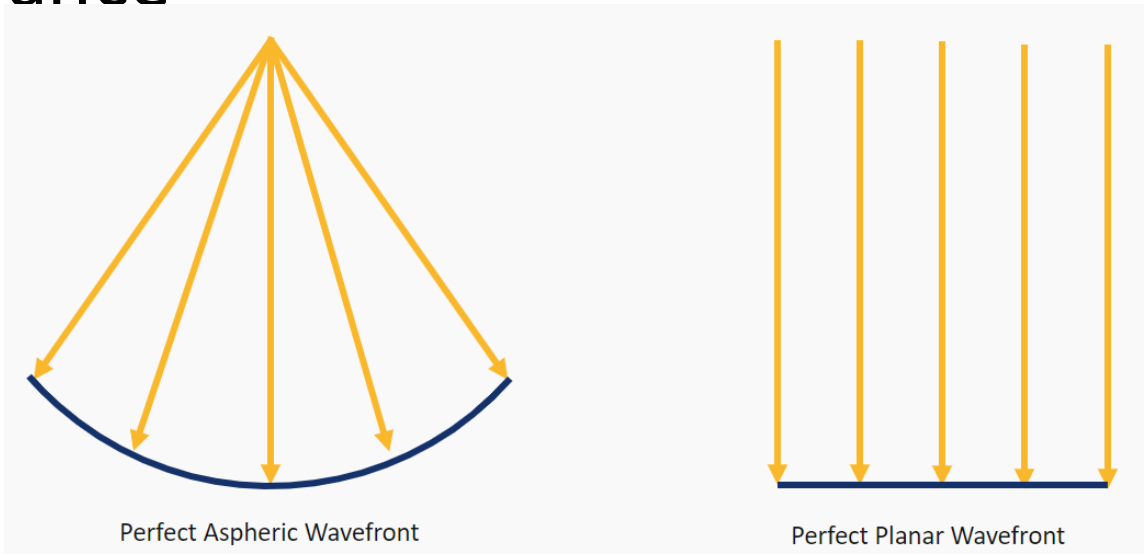
Turbulent Flow / Shockwaves / Separation / Ionization

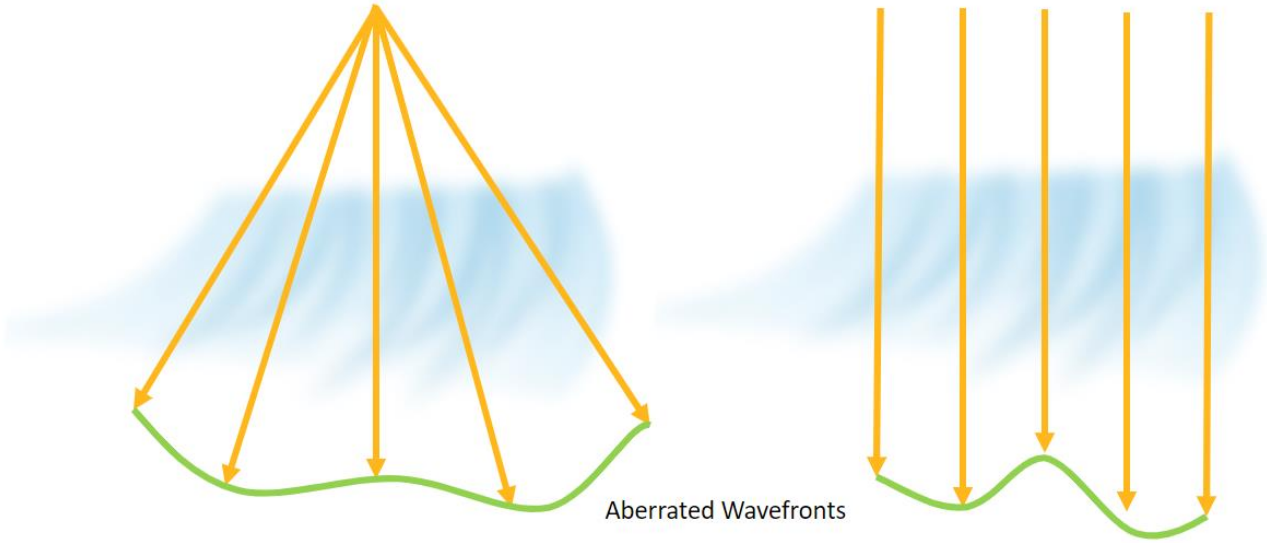
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Effects of Fluids on Optical Performance

- Example of physical changes due to turbulent media:
- Pressure variation
- Temperature
- Density of fluid
- Effects:
- Non-homogeneous refractive index medium.



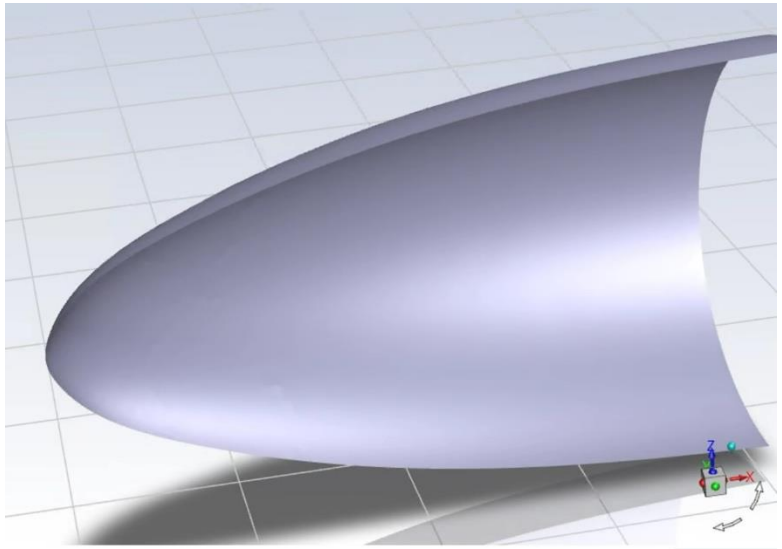


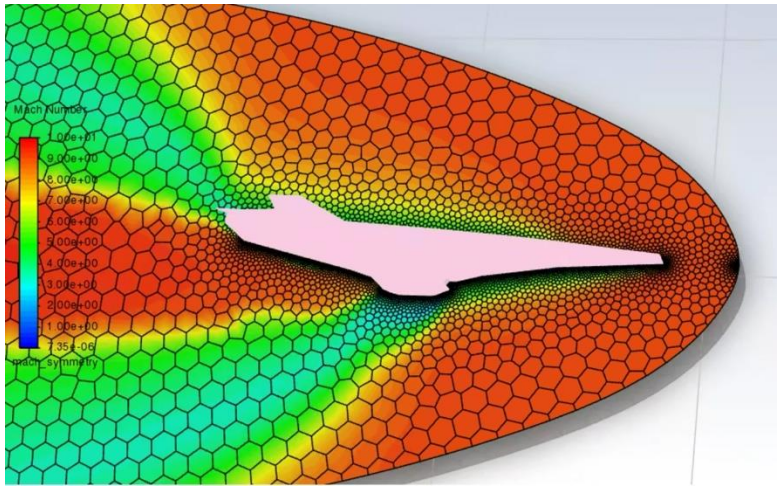


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Go with the Flow

- Please note, that while this training will cover some elements of Fluent, it is not replacement for fluids courses, the user should explore those trainings on ALH to gain a deeper understanding of the topic.
- The conic sections that are often used in these examples are designed to create a volume which is large enough to reduce unwanted artifacts such as edge effects, whiles keeping the volume as small as possible to reduce the computational resources needed.

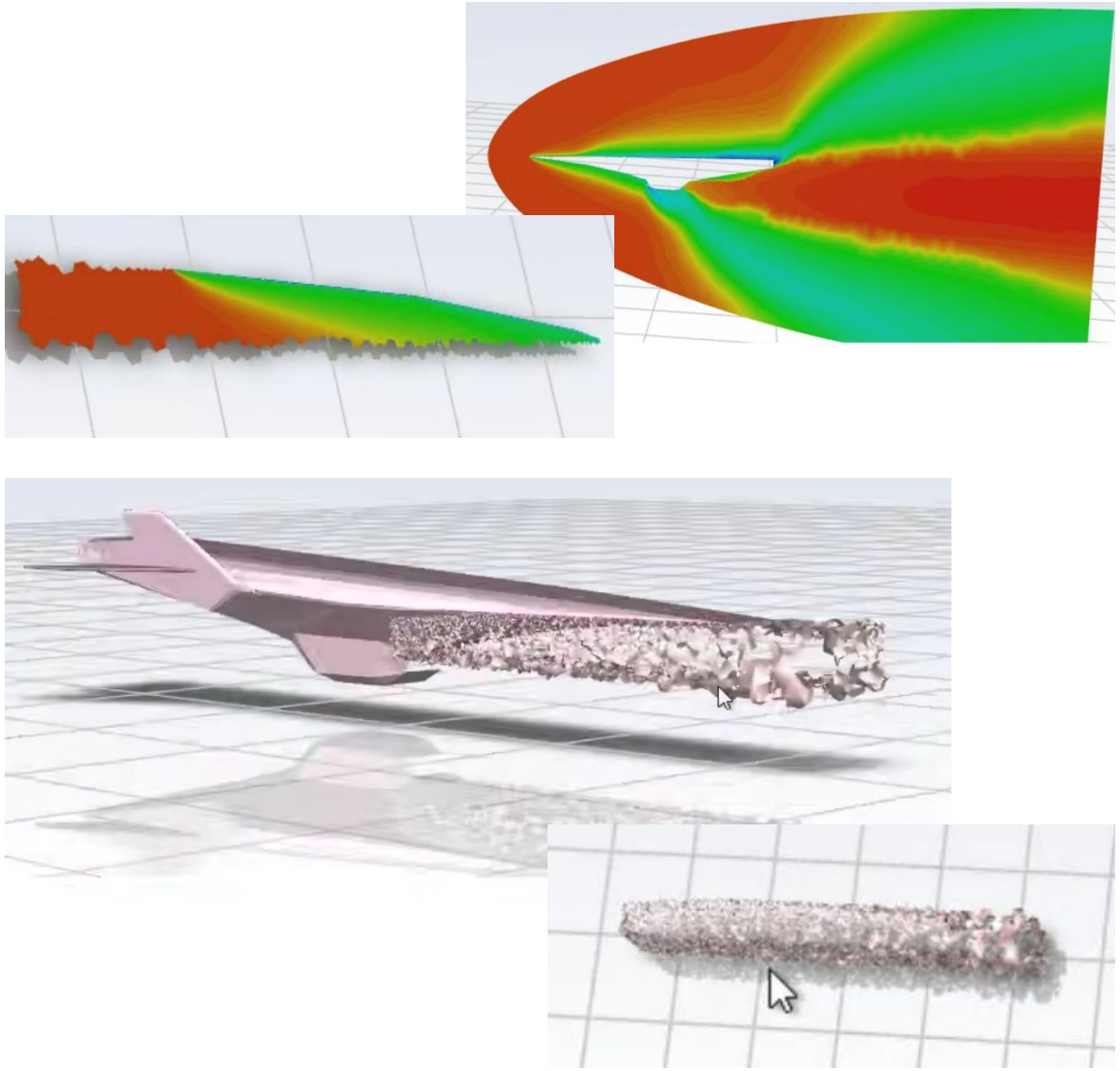




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Named Regions

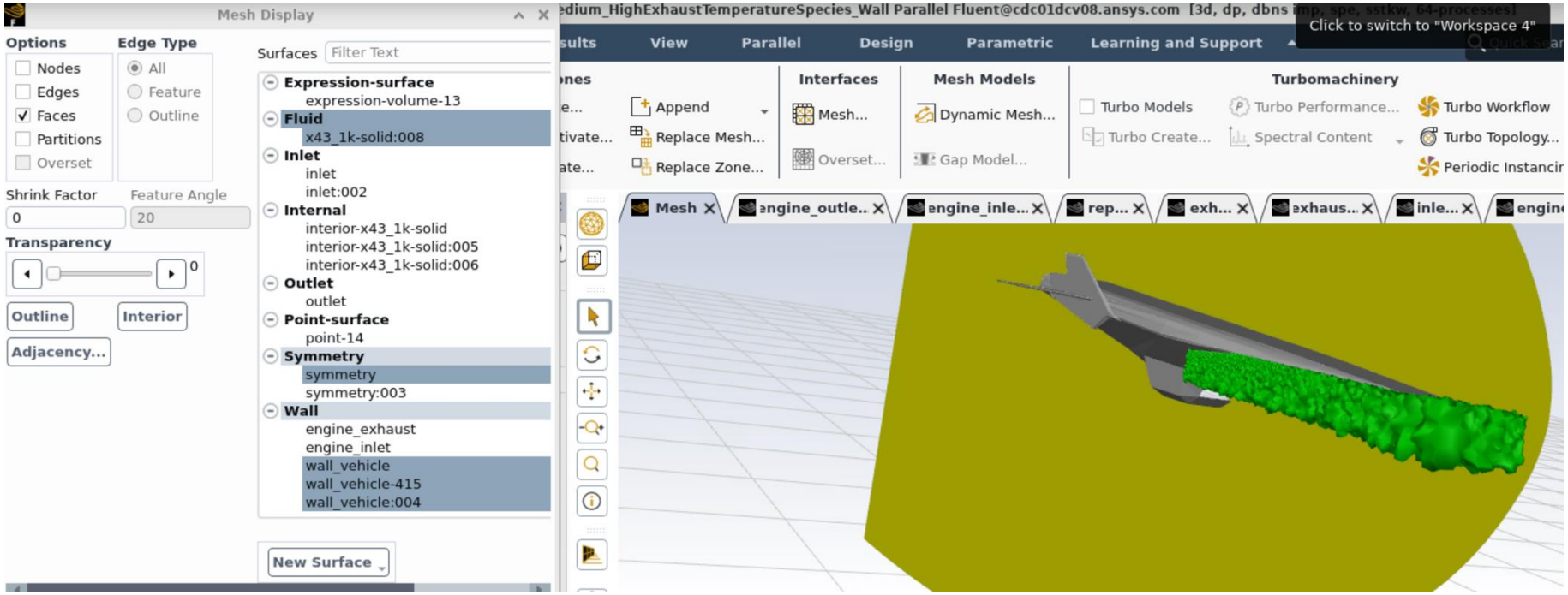
- Named regions allow parts or subsections of the model to be exported or viewed separately for the rest of the system.
- This can be useful for analysis, as it allows different parts of the model to display different properties and it also keeps file sizes smaller when transferring data to other programs.
- In our model, we want only the section of the fluid that coincides with optical path.



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Fluids & Walls

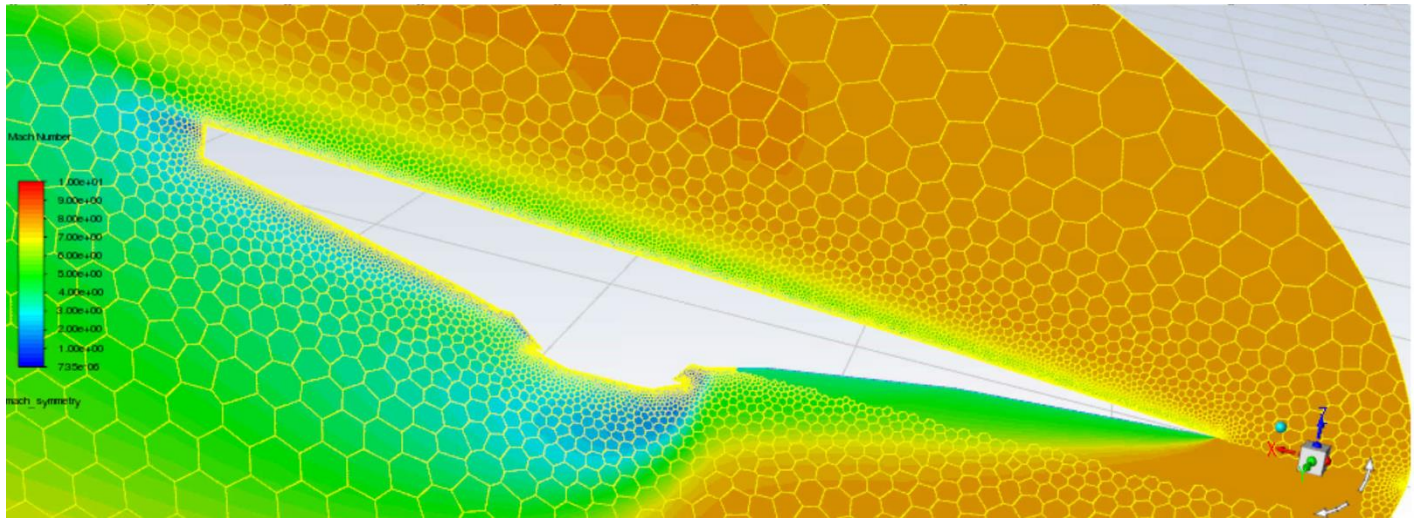
- In our example the area in green is named X43_1k-solid-008 and it is a fluid region. We will use this region later with the Direct Index fitting.
- The X-43 vehicle is made up of many facets and grouped as walls, the three highlighted are the walls we need for mechanical.



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Mesh Control

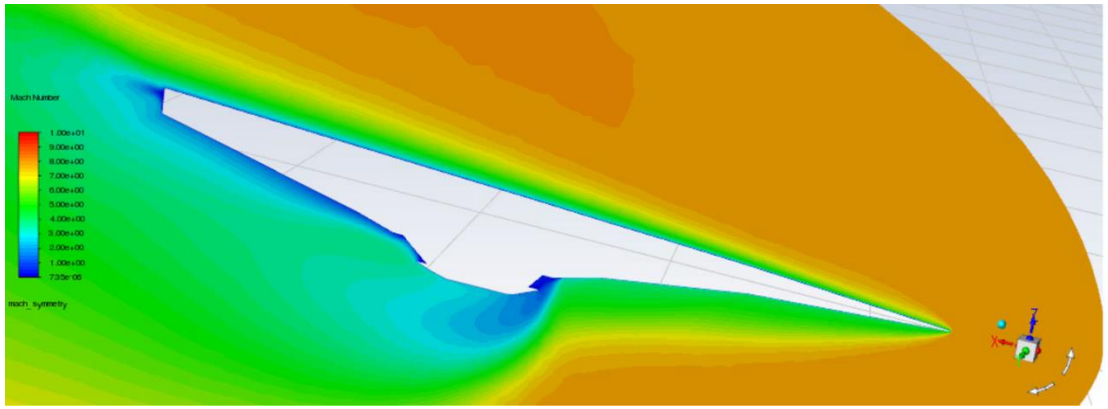
- Fluent can leverage mesh control, this allows the mesh to be fine in areas where hi fidelity is needed and sparce in areas where lower fidelity is sufficient.
- This feature keeps files sizes computationally manageable while still providing the required level of detail.
- This feature can be used with in conjunction with our optical tools. STAR in Zemax OpticStuido Enterprise can accommodate non-uniform data sets.

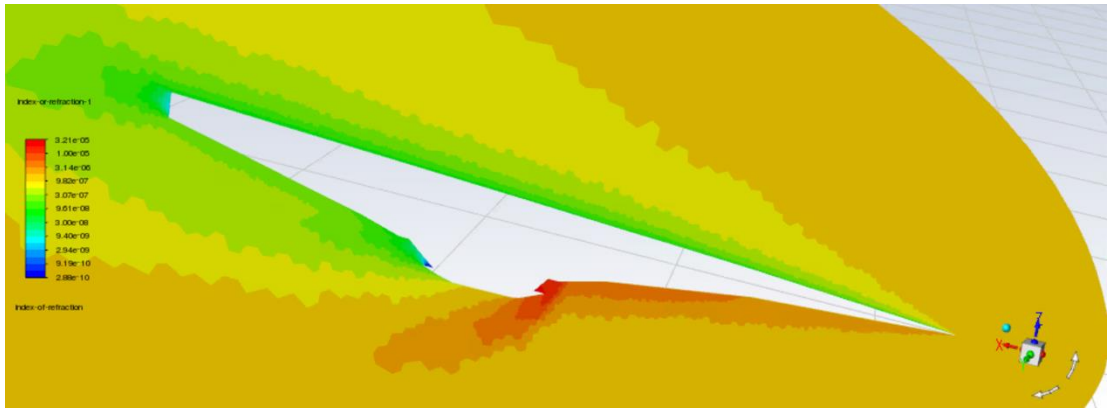


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Fluent: Powerful CFD Tool

- Fluent can display many things, that may provide insight prior to exporting data to other programs.
- The images to the right illustrate the relationship between velocity and the index of refraction.
- Using analysis inside the CFD tool can save a lot of time prior to exporting for deeper optical analysis and can help identify the items to be exported.

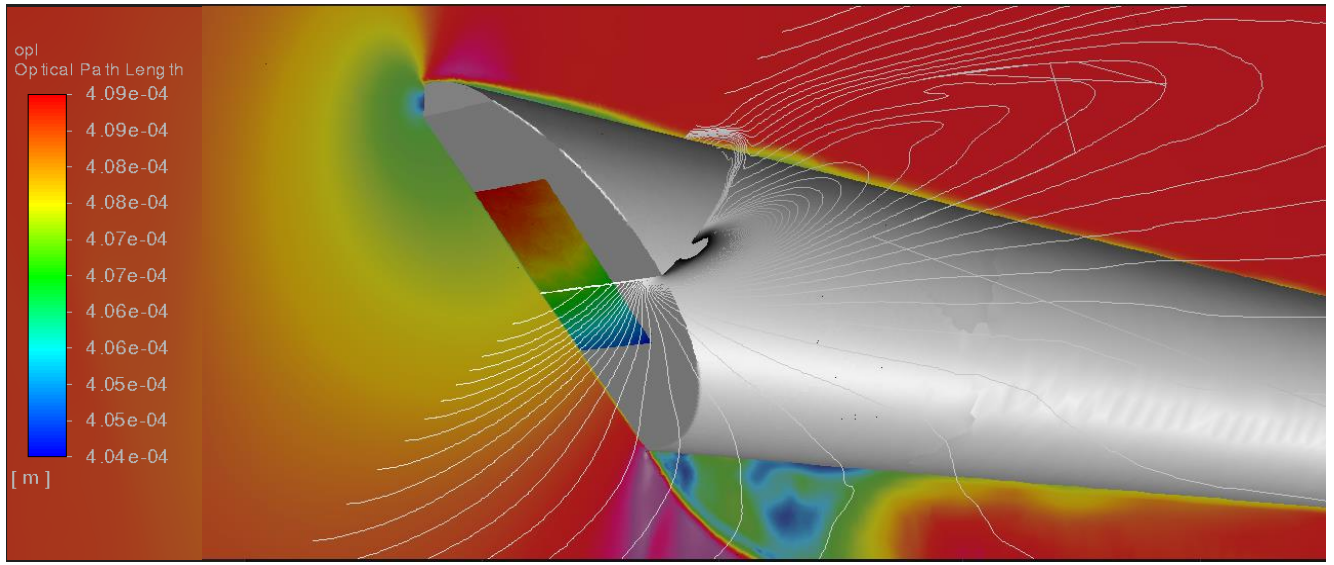




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Fluent: Powerful CFD Tool

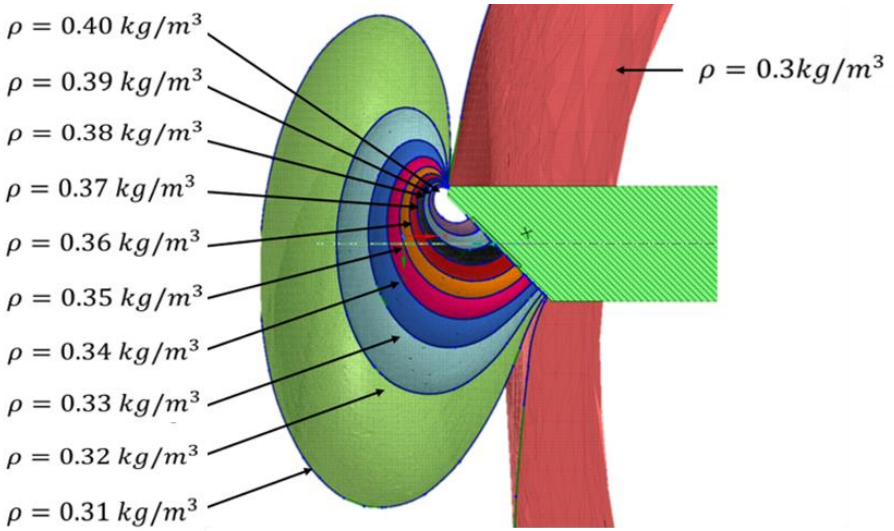
- The power of One Ansys is that we can add functionality to multiple items simultaneously to facilitate a continuous workflow. For example, we have added fluid functionality to optics and we have added optical functionality to fluids.
- The example below displays the optical path length, Fluent can display OPL / OPD, Optical Path Length and Optical Path Difference. It can also show these optical properties as a transient. This allows the critical time steps of interest to or specific conditions to be more readily identified.



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Steady State CFD Analysis

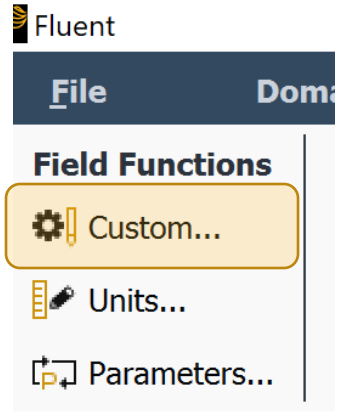
- Obtain the Refractive Index
  - File contains the index of refraction
  - Use any custom equation such as: Gladstone-Dale, Lorentz-Lorenz, and Kramer-Kronig
- Export this data for optical use with:
  - Custom field functions
  - ACT scripts
  - Python

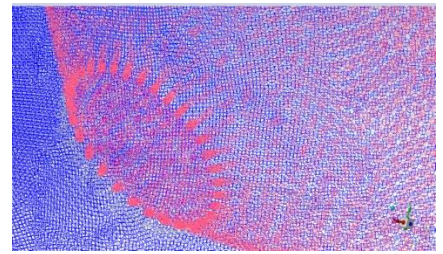


$$\frac{n-1}{\rho} = \sum_{i=0}^{n} k_i m_i$$

$$n_\lambda = 1 + \frac{1}{2\pi^2}\mathcal{P}\int_0^\infty \frac{\alpha_{\lambda'}}{1-\left(\frac{\lambda'}{\lambda}\right)^2}\,d\lambda'$$

$$\oint \frac{\chi_{\omega'}}{\omega' - \omega}\,d\omega' = 0$$



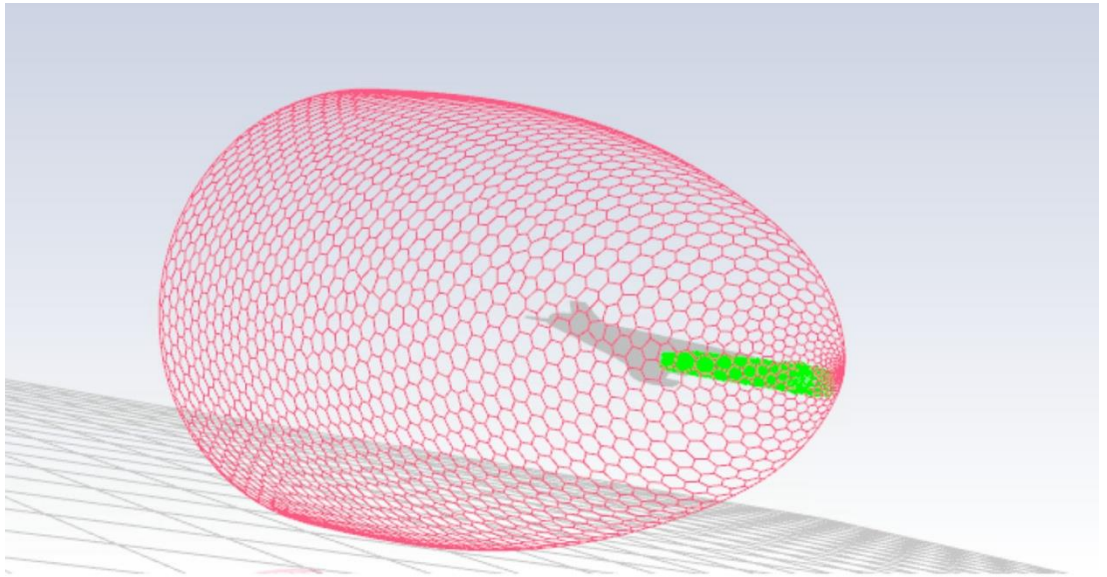


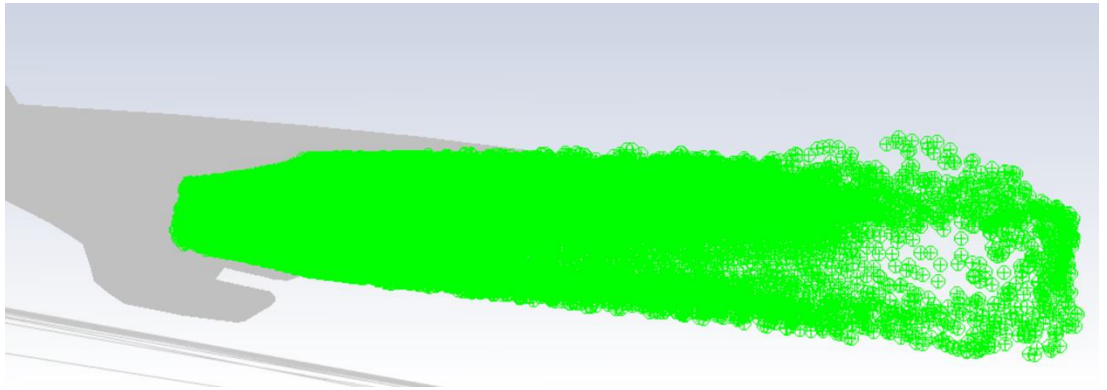
Custom Equation Unique to the Conditions → Custom Field Functions → Export Point Cloud from Nodal Data

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Export Flow Field Data

- Use the named regions to export only the regions of data that are of an optical interest. These regions are what will be imported into Zemax OpticStudio Enterprise, using the Direct Index feature within the STAR tool.
- The goal is to keep the files as small as possible while still containing the level of fidelity needed for the optical system.
- In this example while the flow field is large shown in red, the area of optical interest is small displayed in green.

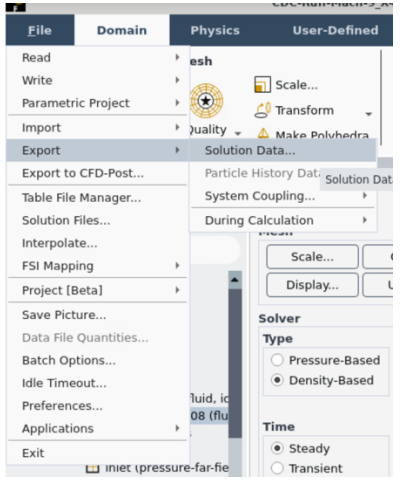


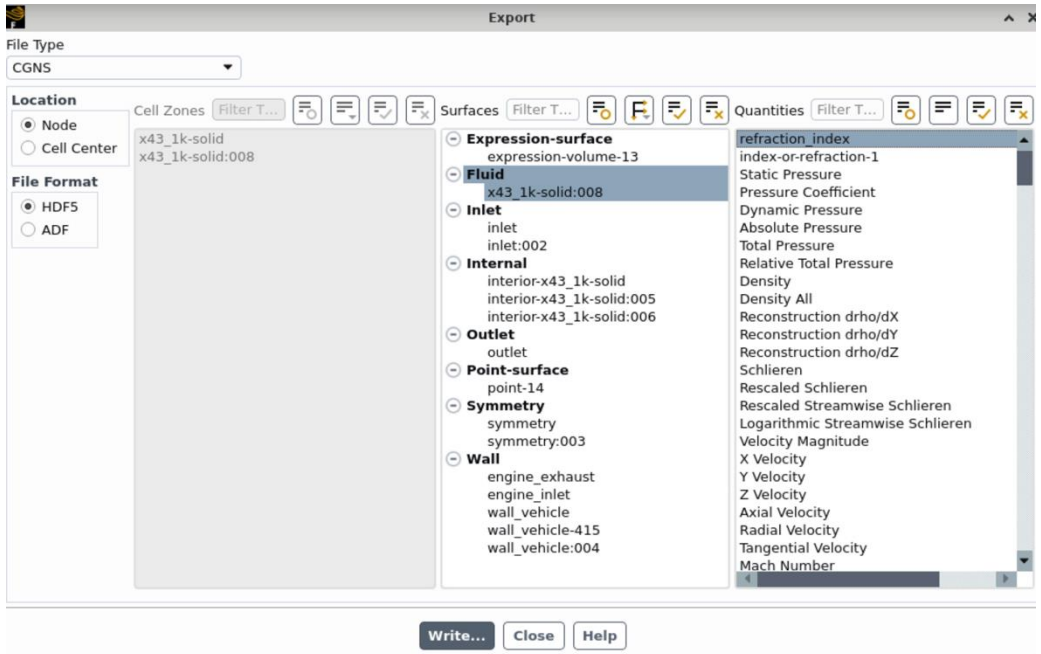


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Exporting Optical Data from Fluent

- There are number of items that may be needed when exporting Fluent data for optical analysis, depending on the analysis to be performed.
- Exports can be made as either Nodes or Cell Centers, Nodes are the vertices points of the mesh and Cell Centers are a point value in the center of the three dimensional cell.
- For this example the following is needed.
  - Refraction_Index
  - Note this is not one of the standard variables offered for export within Fluent, this is a user defined variable that was entered using the custom field function.





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Symmetry Tool

Reduce Computational Time / Reduce File Size

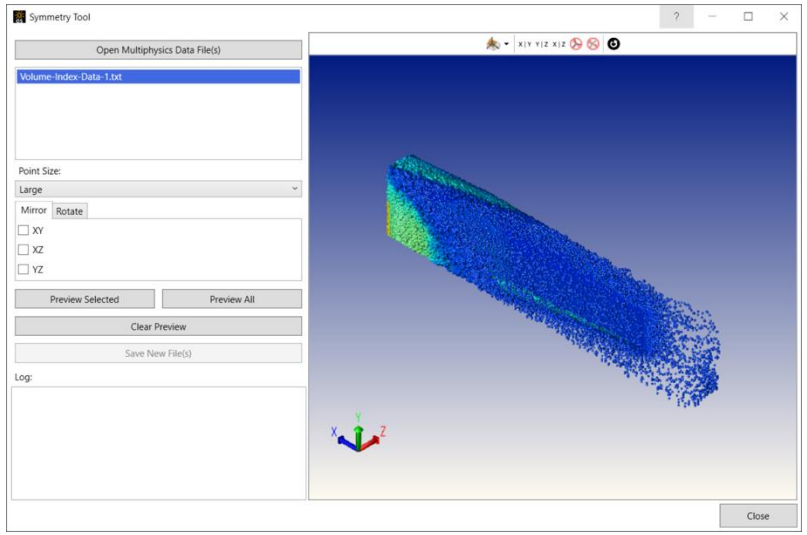
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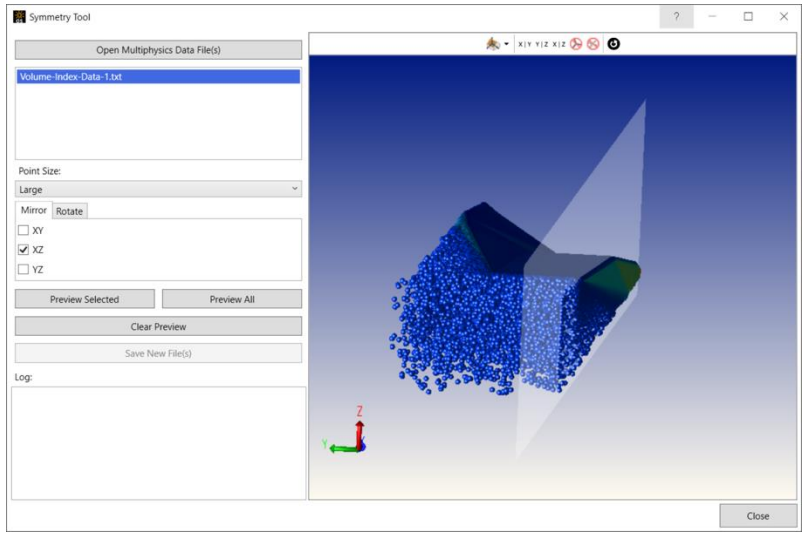
Symmetry Tool

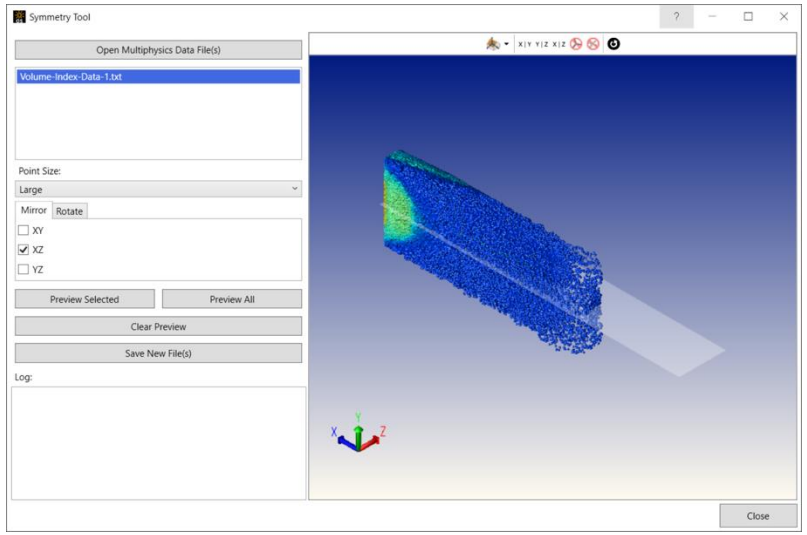
- When symmetry exists in a system, exploiting it can reduce computational time.
- The symmetry tool for fluids works in the same way that it does for mechanical data.
- The tool allows symmetry in systems to be exploited to reduce computational resources.
- Note if no symmetry exists in the system of interest, the STAR tool will still work, but the symmetry tool should not be used. Instead, the full volumetric point cloud will need to be imported, not a partial data set.

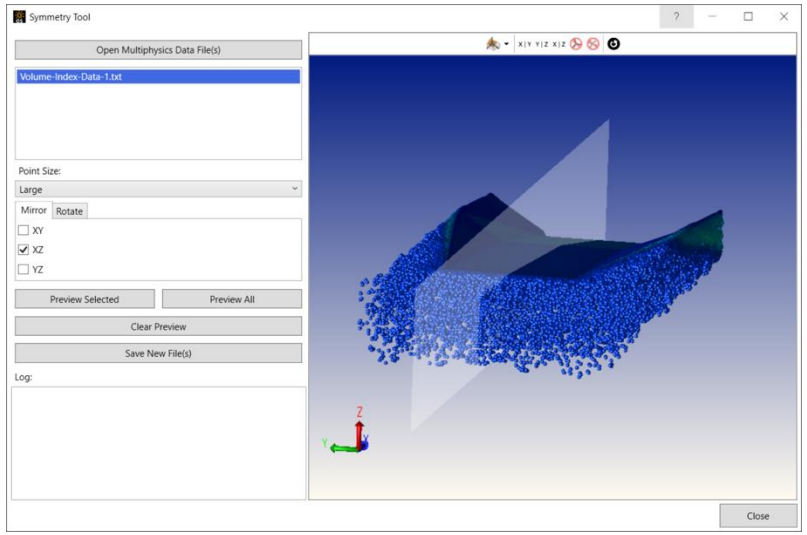
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Symmetry Tool





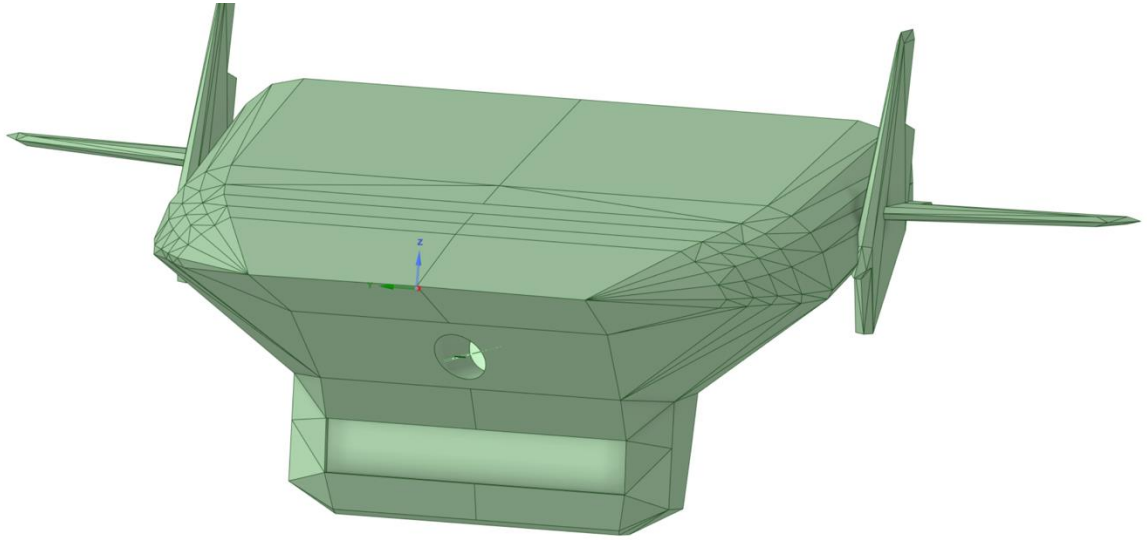


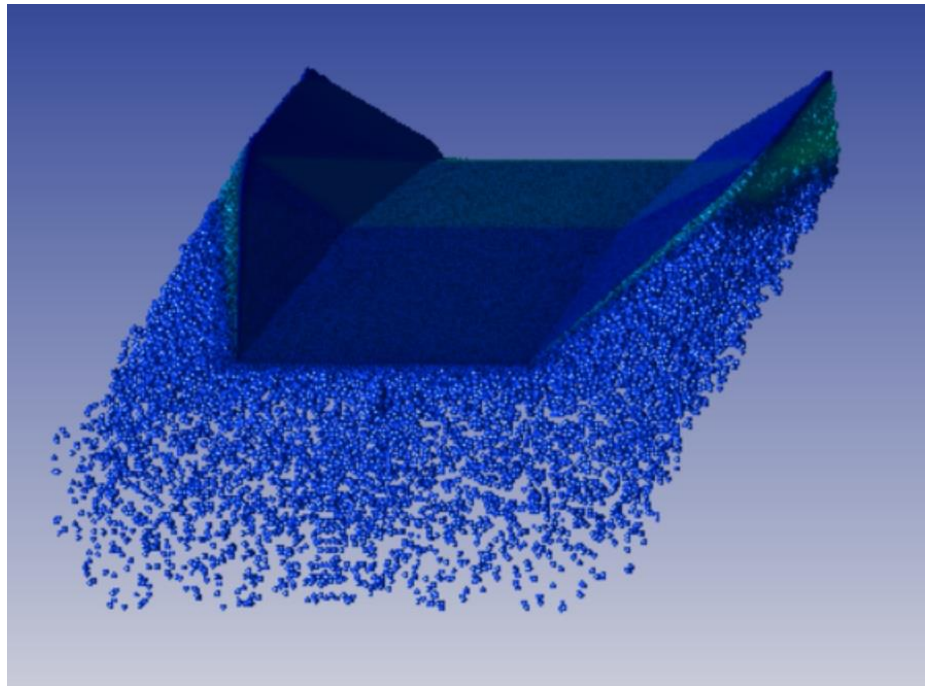


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Sanity Check

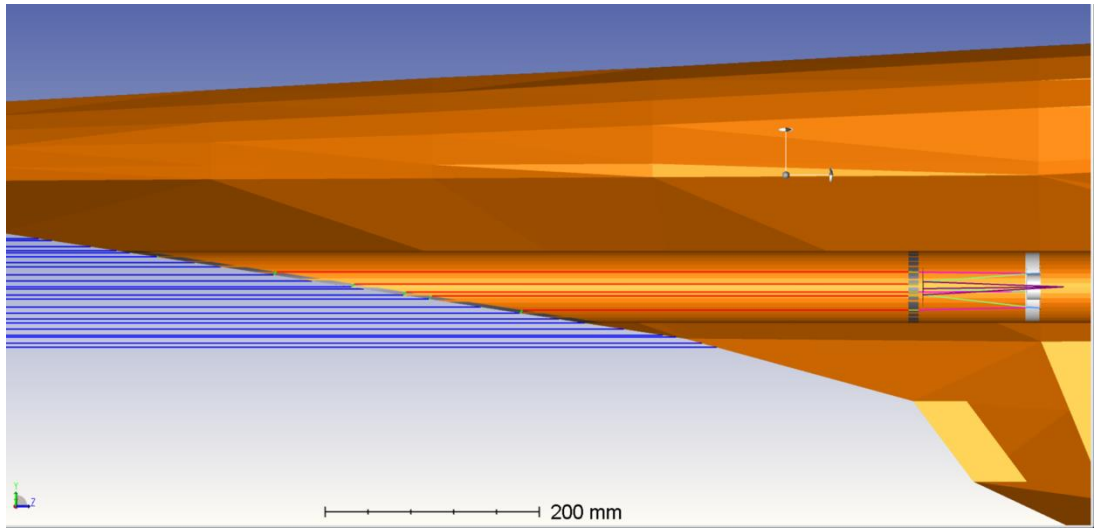
- Visually confirm that the shape of the CAD object and the shape of the fluid volume make sense for the given system.
- In this case, the point cloud on the right represents the volume of air under the vehicle on the left. The shape the vehicle makes in the fluid is apparent.

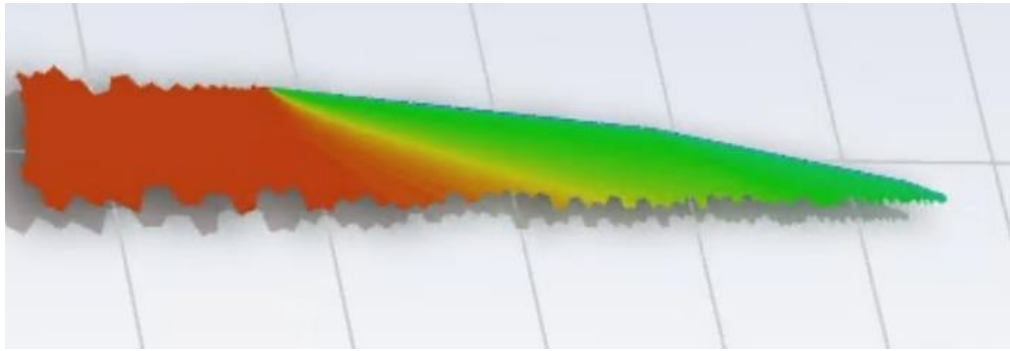


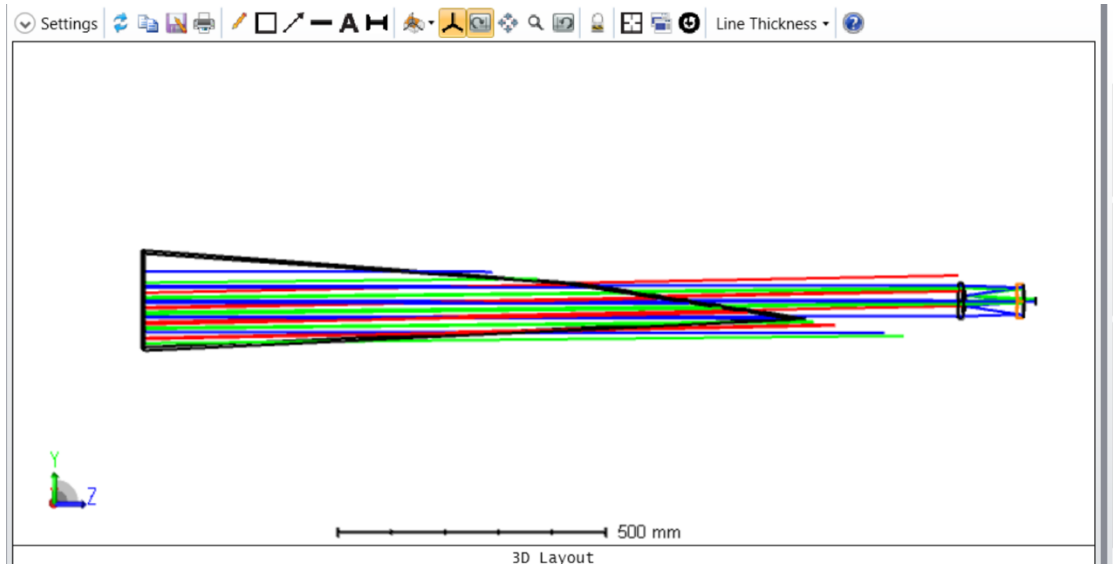


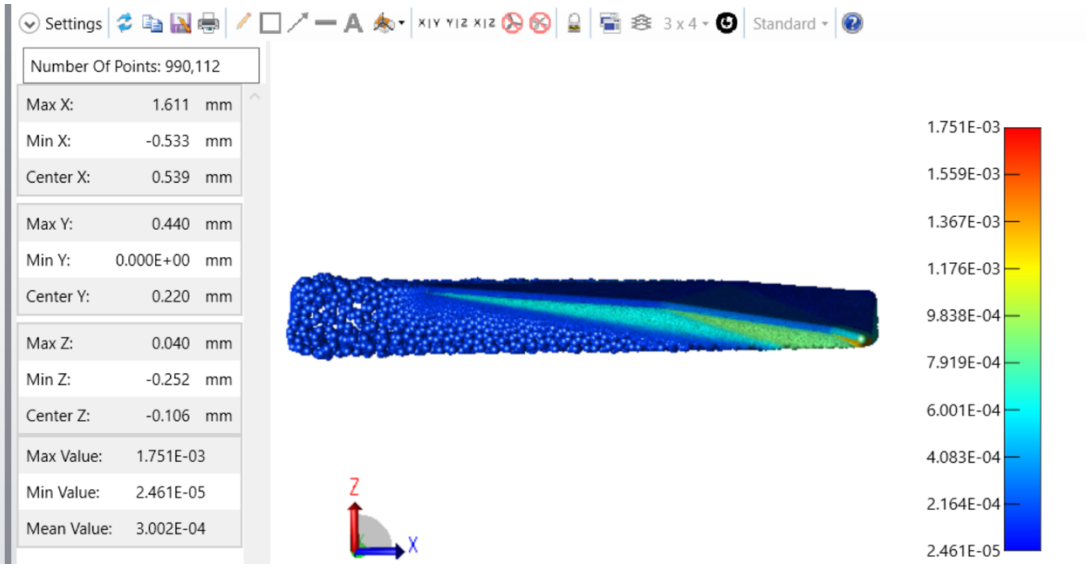
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Sanity Check









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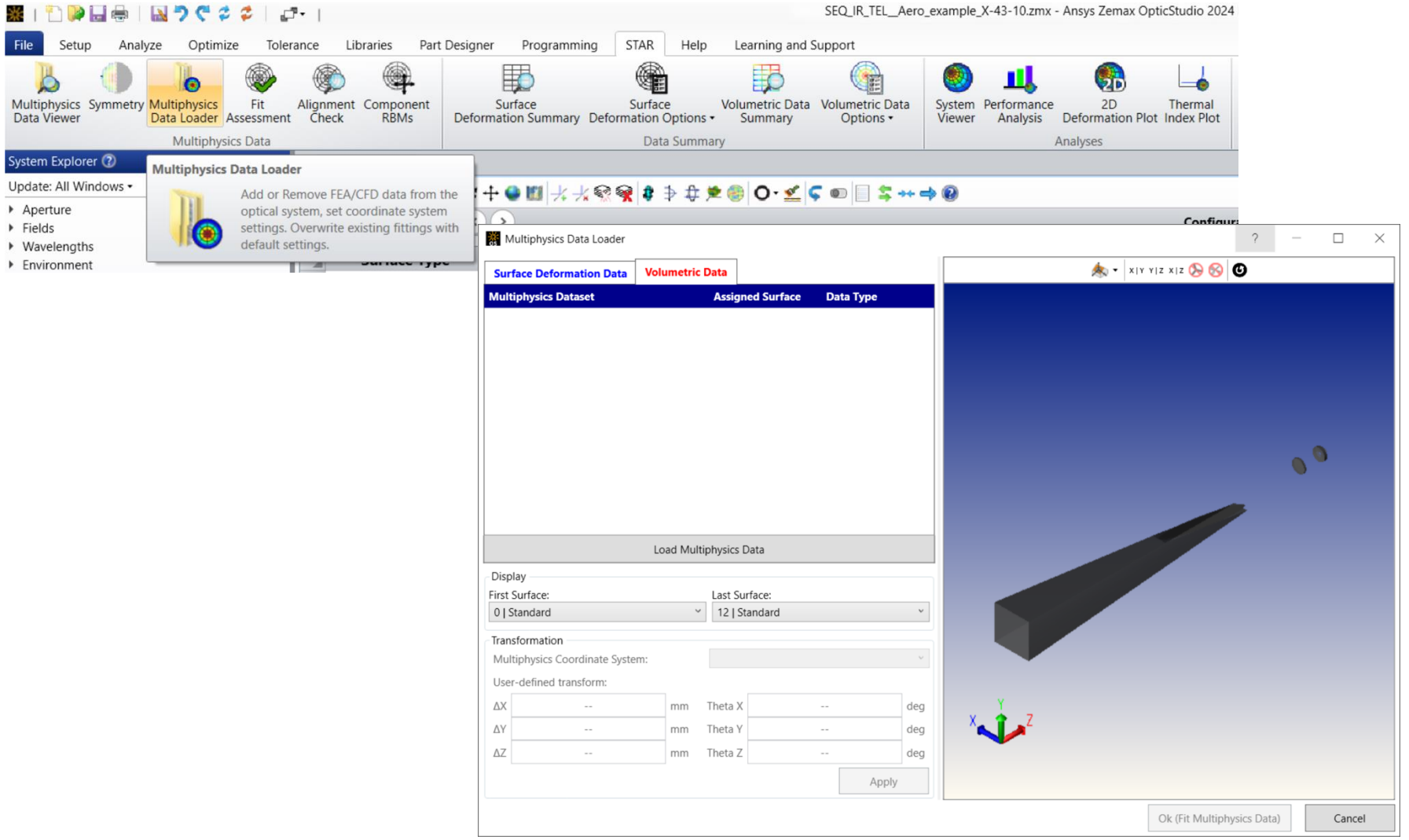


Multi-Physics Data Loader

Import / Align / Fit

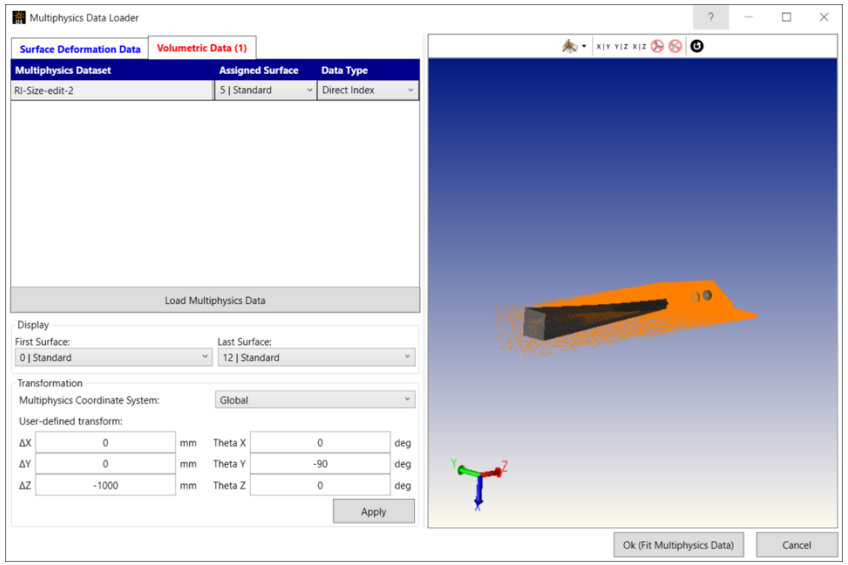
©2025 ANSYS, Inc.

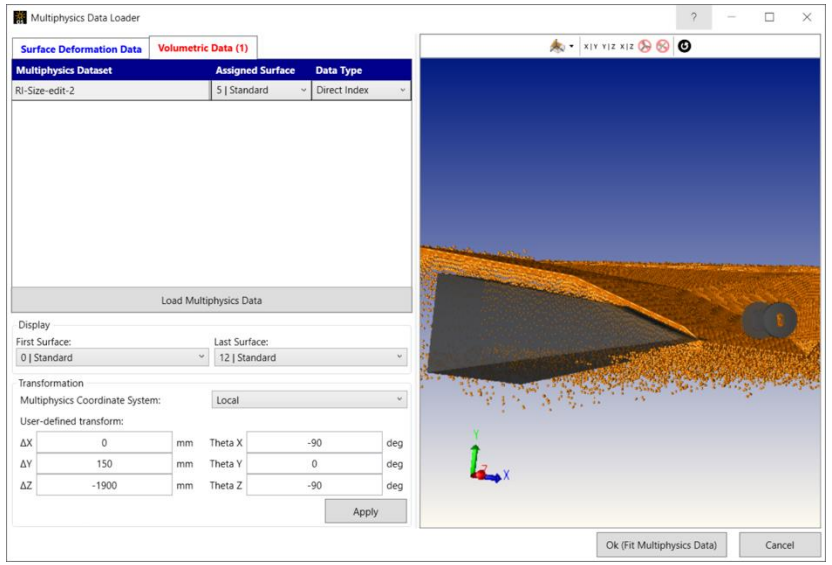
Multi-Physics Data Loader

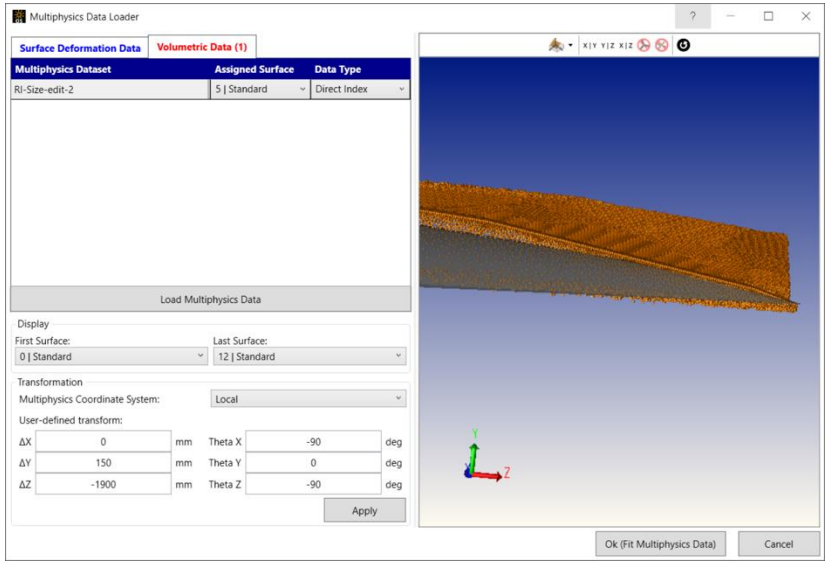


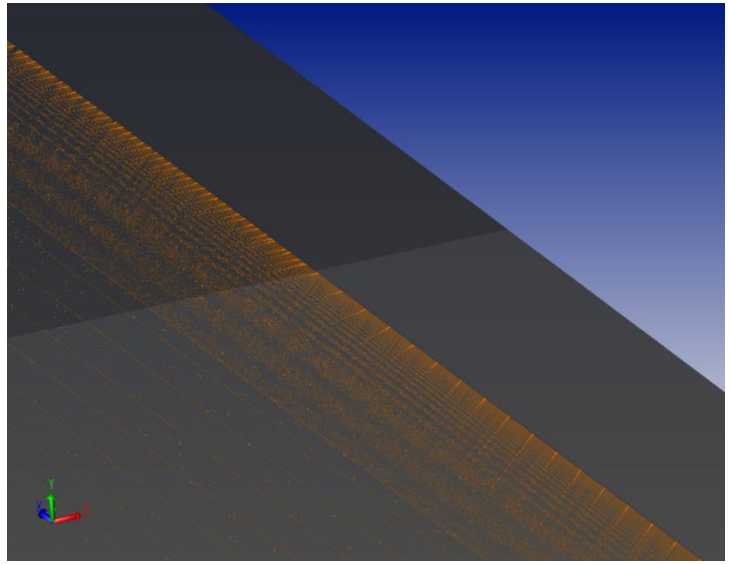
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Loading Point Cloud Data to the Dummy Volume









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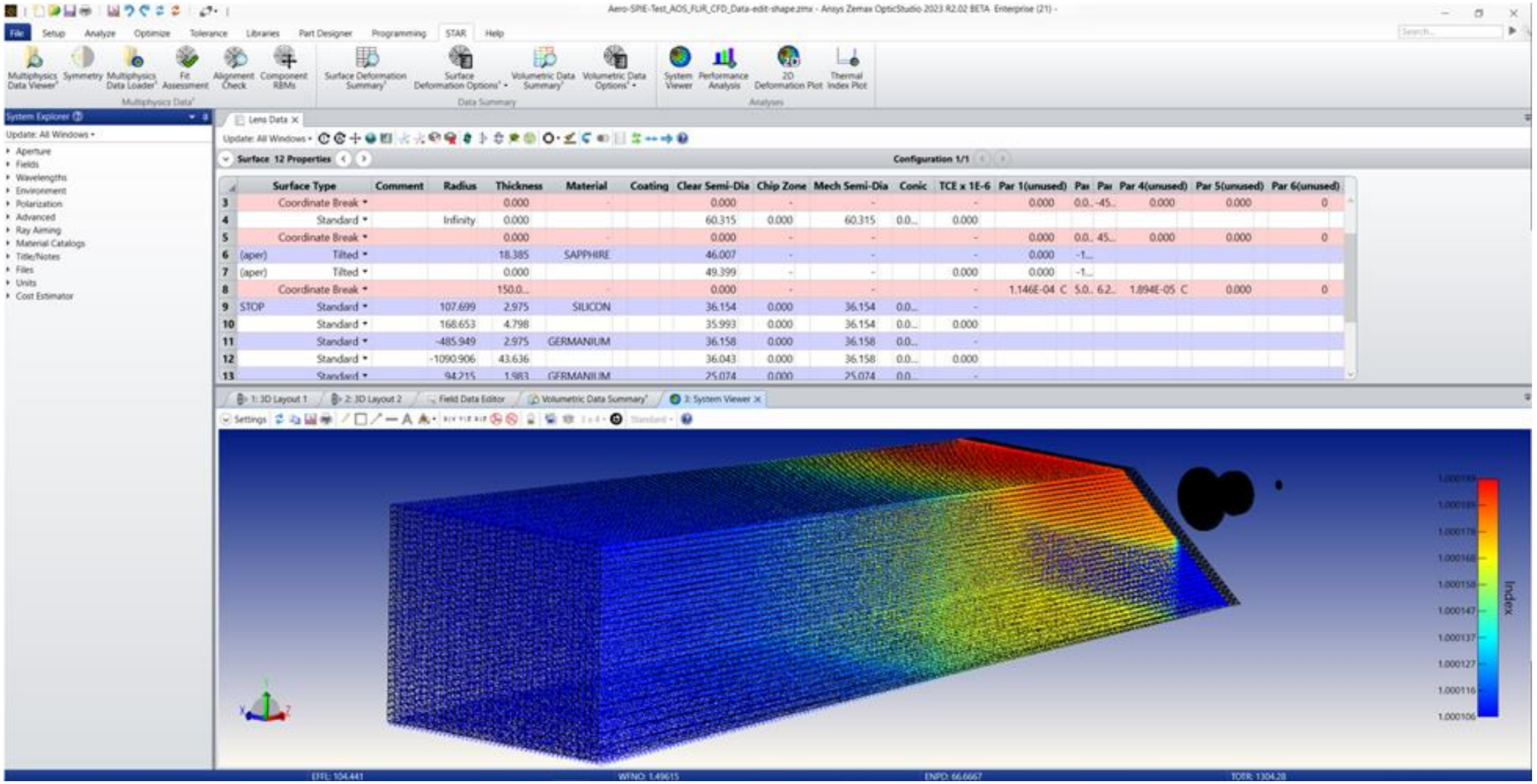


Multi-Physics Analysis

Performance Metrics / Image Simulation / Visualization

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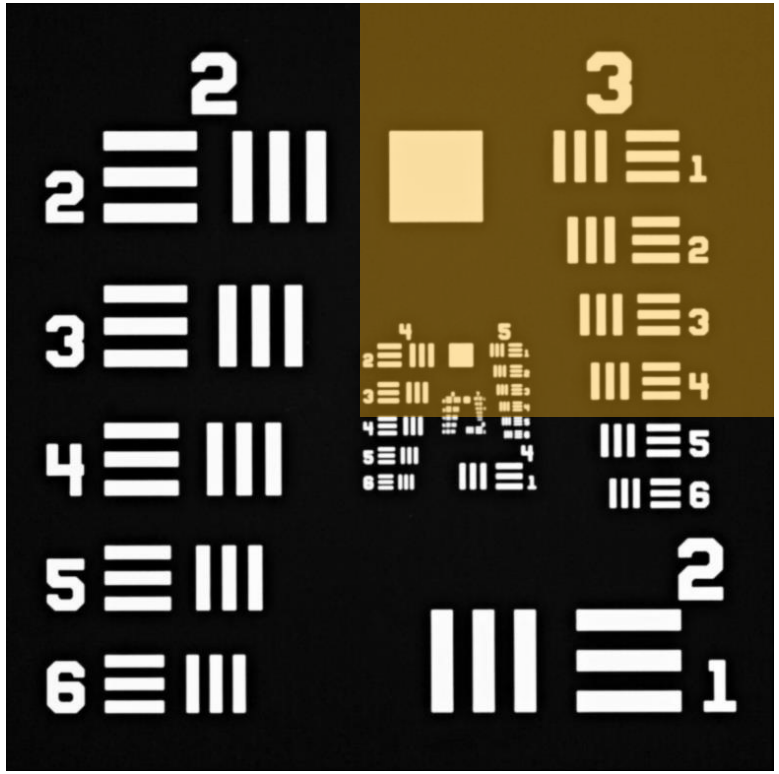
Fitting the CFD Volumetric Data



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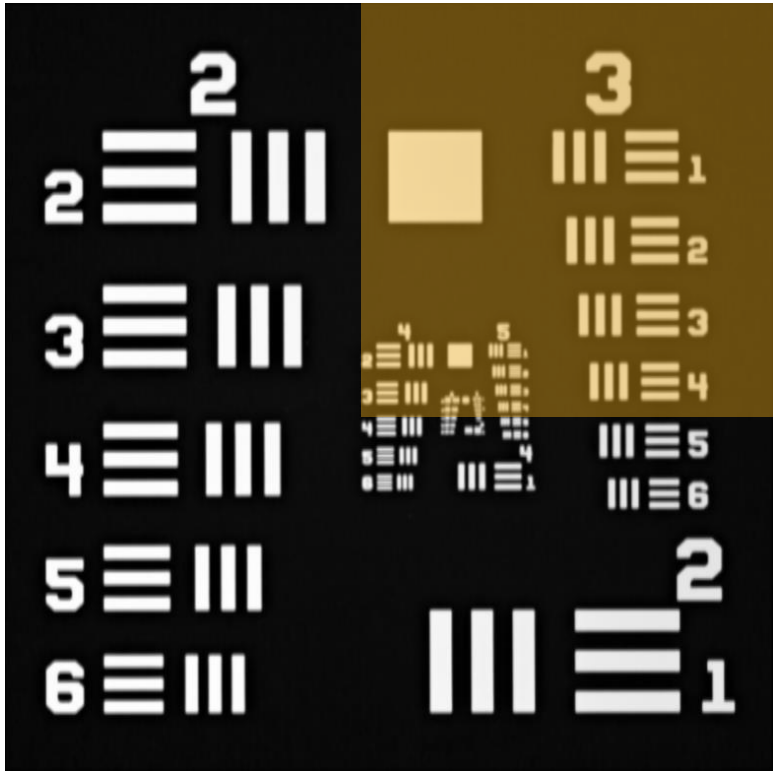
Aero-Optics Results

Image Nominal



Nominal Performance

Image AeroOptics

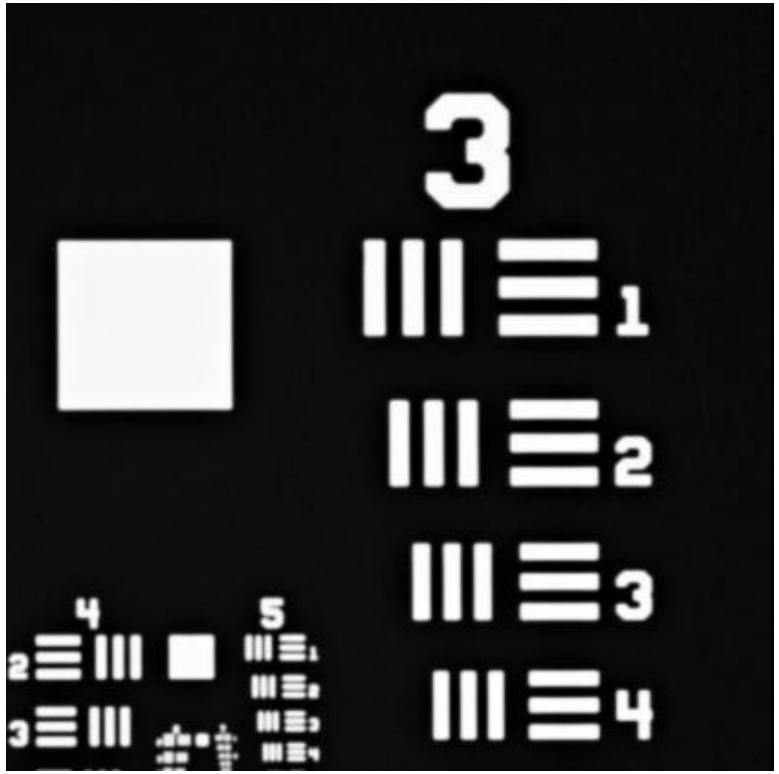


alpha : 5.3 deg
beta : 1.52 deg
Mach Speed : 1.2
Altitude : 30,000 ft

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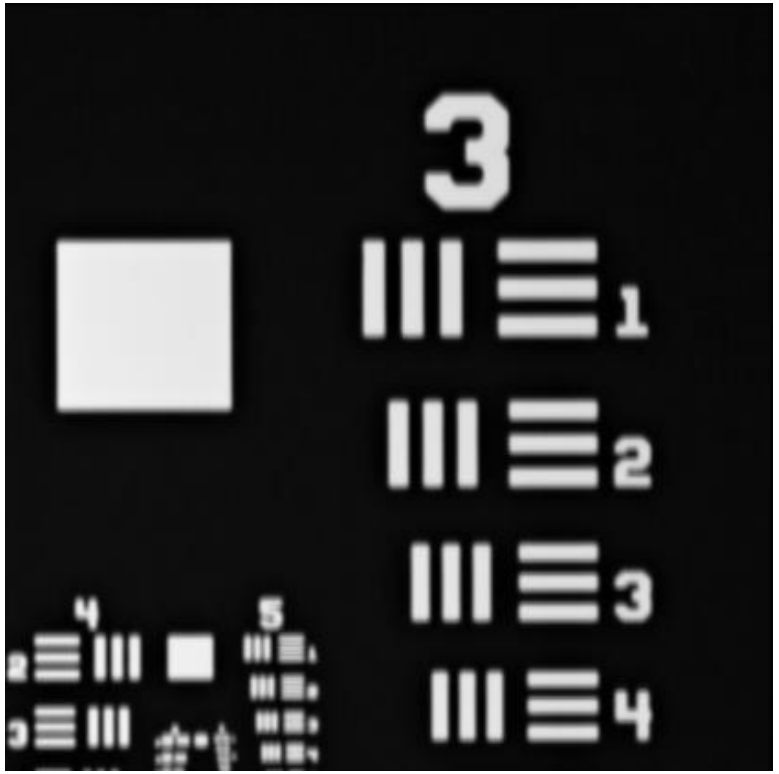
Aero-Optics Results

Image Nominal



Nominal Performance

Image AeroOptics



alpha : 5.3 deg
beta : 1.52 deg
Mach Speed : 1.2
Altitude : 30,000 ft

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Various Multi-Physics Optical Degradation to a Synthetic Scene

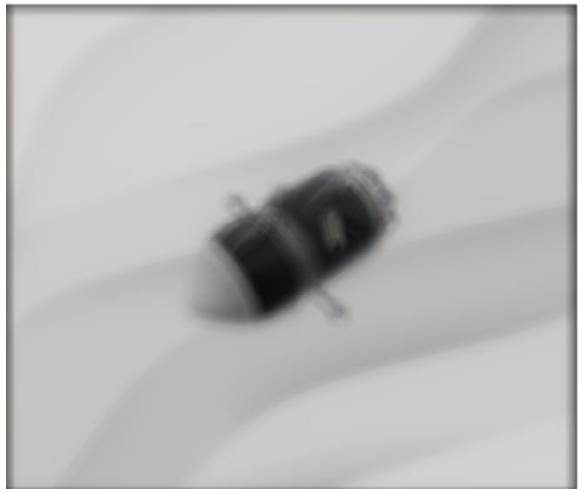
Nominal



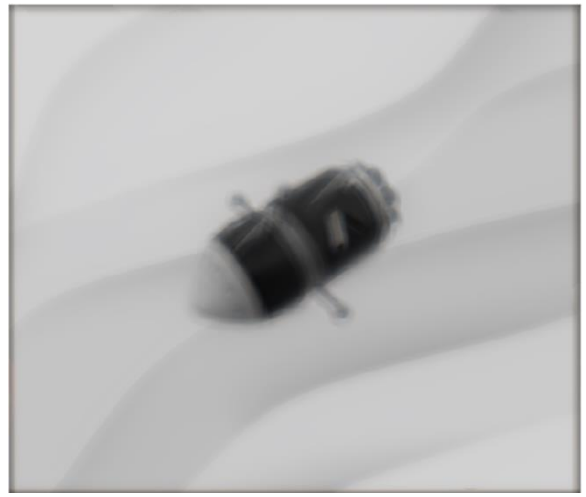
Structural



Thermal



Structural and Thermal



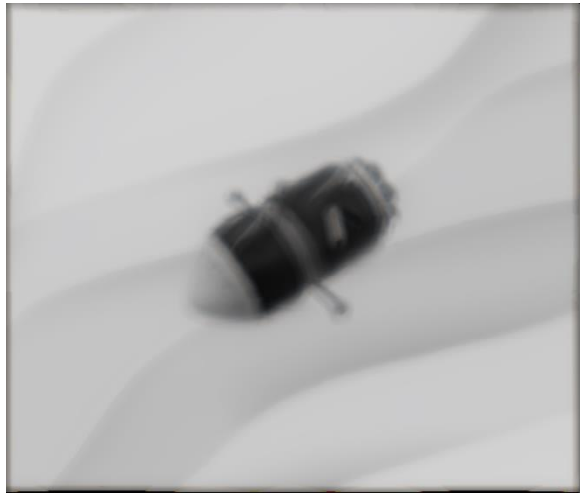
Nominal



Aero-Optics



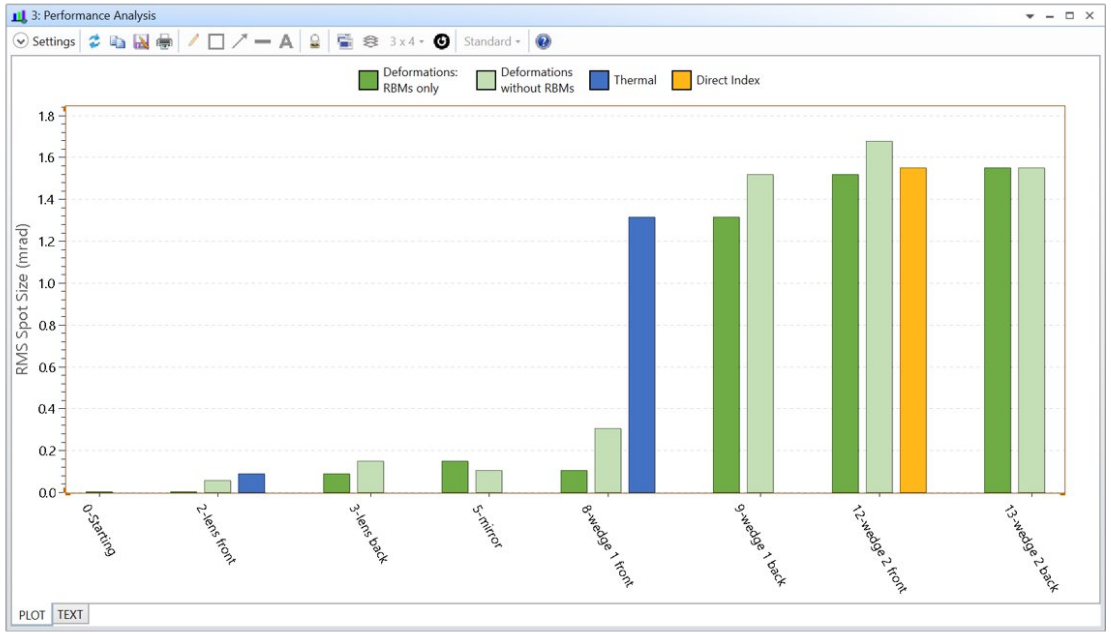
STOP & Aero-Optics



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Performance Analysis

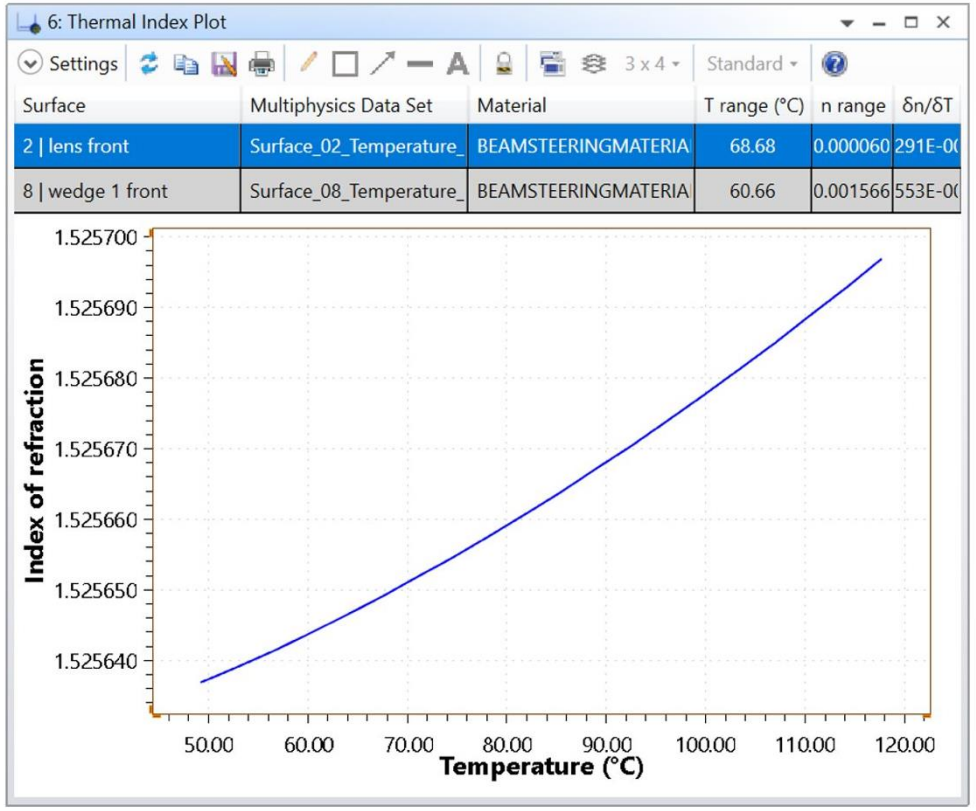
- Understand where the largest change in performance is occurring AND what effect is causing it…very powerful
- Works by turning ON/OFF different datasets and monitoring performance automatically
- Helps customer determine what is having the largest effect



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Thermal Index & Material Selection

- Displays the refractive index vs temperature for surfaces with thermal datasets applied
- Understand the behavior of refractive index over temperature range
- Important information that is automatically provided from STAR



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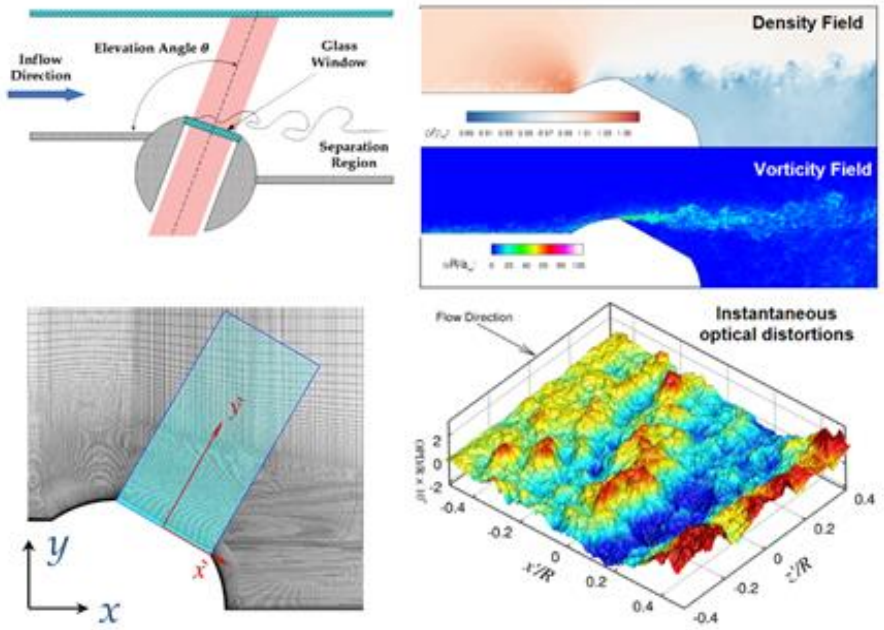


Other Near Field Effects

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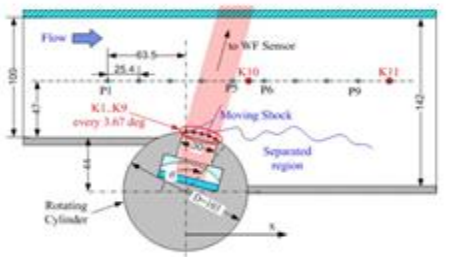
Beam Propagation: Aero-Optical Simulation

Subsonic Flow Over a Cylindrical Turret

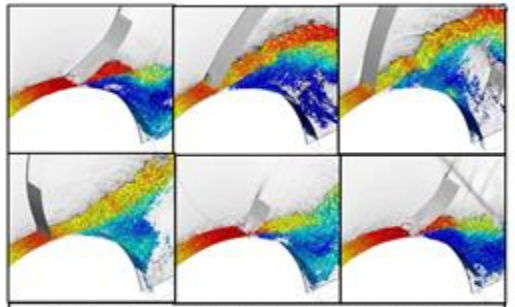


Kamel et al. AIAA Paper 2016-1462 & Kamel M., PhD Dissertation 2017

Transonic Flow over a Cylindrical Turret with shock/wake interaction

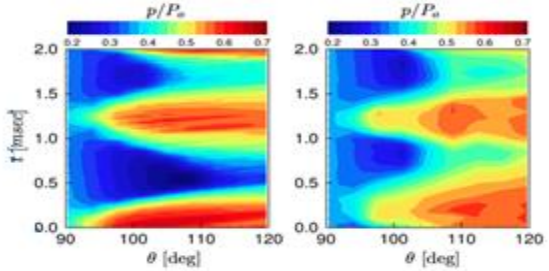


Experimental setup of **Vorobiev et al. (AIAA Paper 2014-2357)**



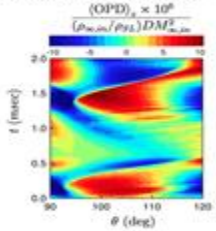
Iso-surfaces of λ_2 criterion colored by streamwise velocity. The shock position is indicated by the grey iso-surface of strong negative dilatation. **(Kamel et al., submitted to AIAA Scitech 2019)**

Instantaneous pressure (Numerical predictions)

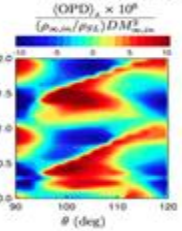


Instantaneous pressure (Exp. Measurements)

Spanwise-averaged OPD Numerical predictions



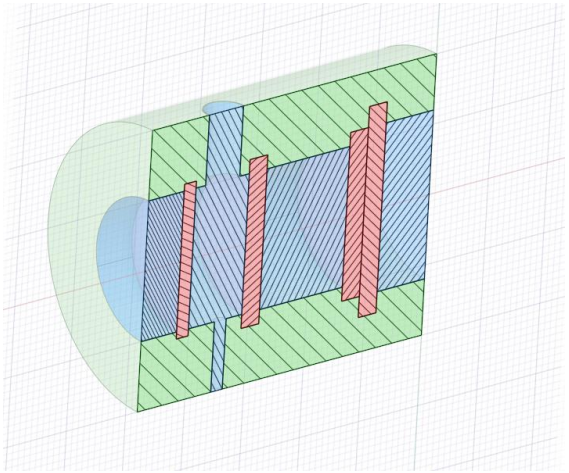
Spanwise-averaged OPD (Experimental measurements)

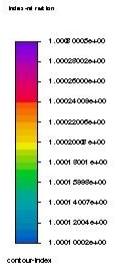


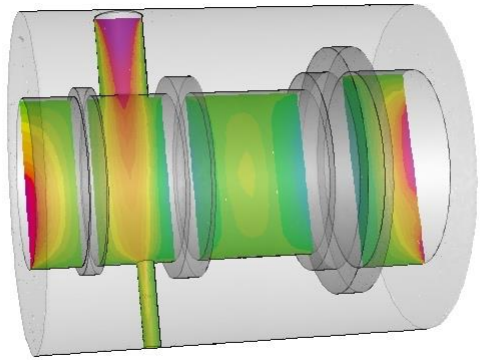
- Aero-optical phenomenon is concerned with the aberration effects of turbulent flow induced by solid surfaces near the projection or viewing optical aperture
- Fluctuations in turbulent density field cause fluctuations in the index of refraction field as described by Gladstone-Dale relation

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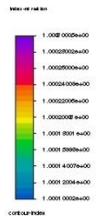
Cooling

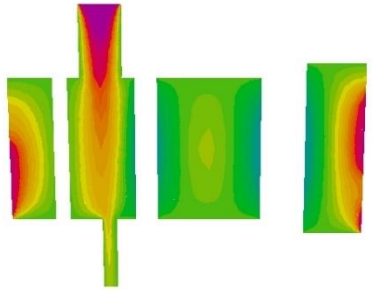




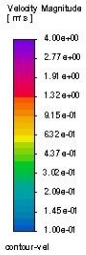


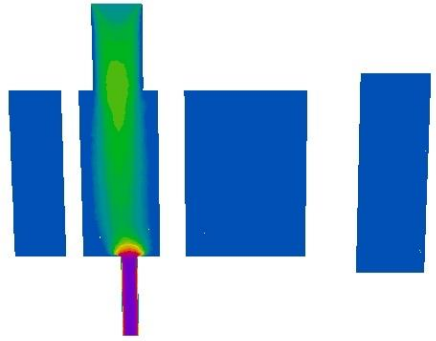














- Cooling with bursts of CDA (Clean Dry Air)
  - When the bursts are at low pressure or velocity, the flow is more laminar and the optical aberrations are minimal
  - When the bursts are at high pressure or velocity, the flow is turbulent and the optical aberrations are significant

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Far Field Effects

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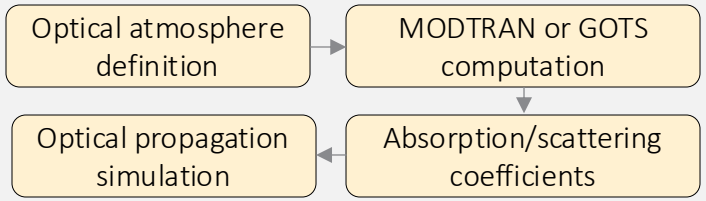
Beam Propagation: Atmospheric Distortion and Attenuation

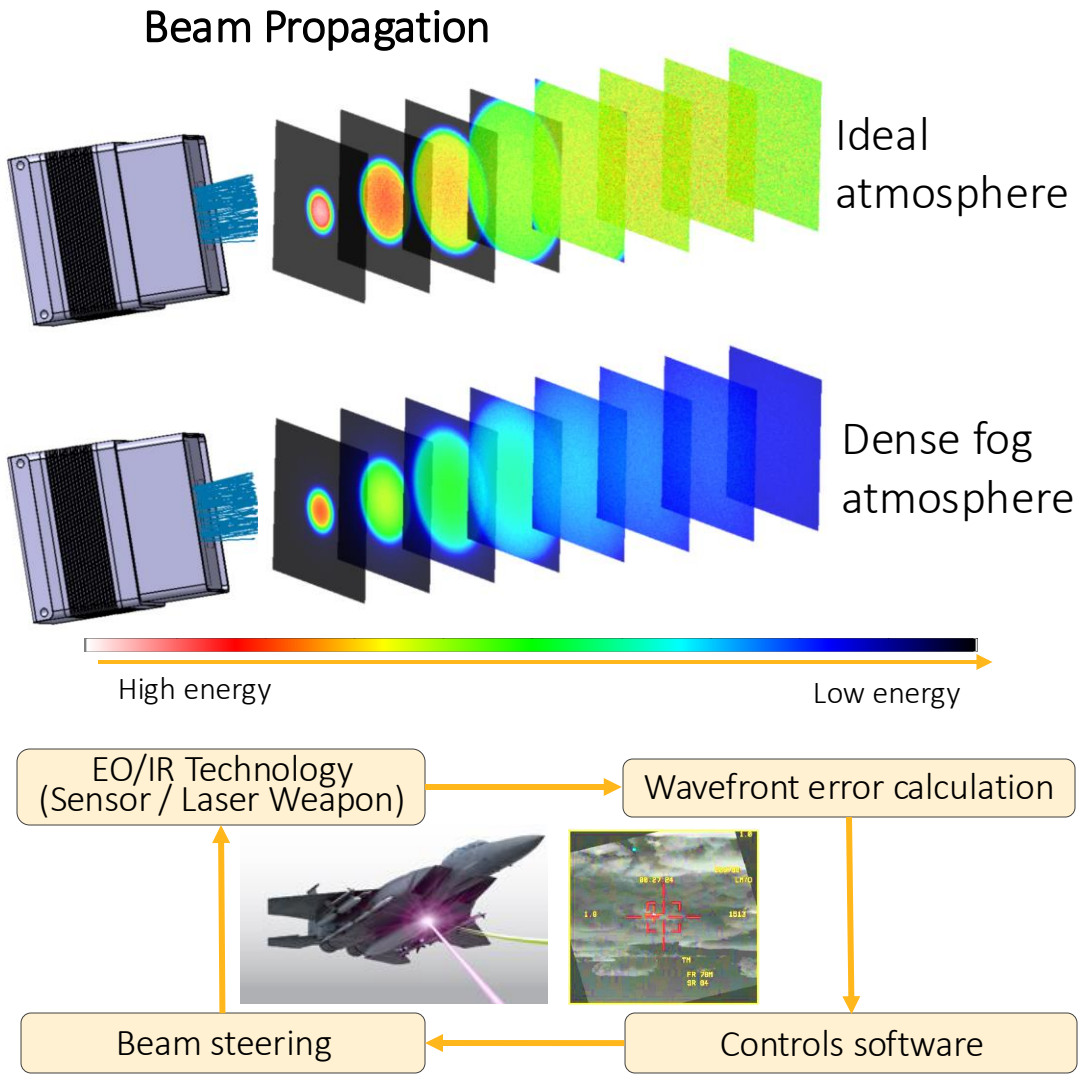
Source definition from output area of laser unit, considering:

- Source energy and spectrum
- Asymmetric Gaussian beam profile
- Spatial distribution across emission surface

Beam propagation through atmosphere using MODTRAN code:

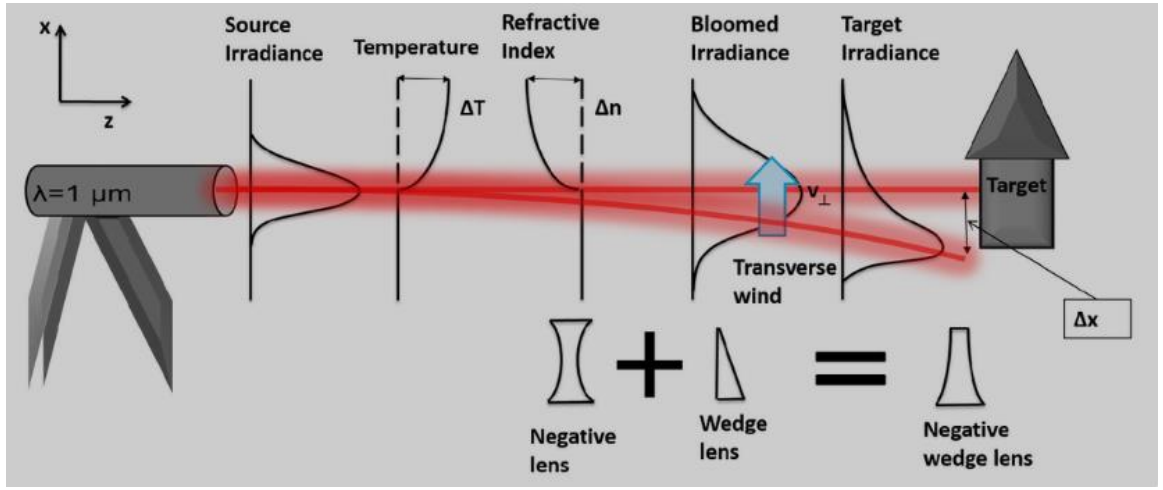
- Computes linear propagation loss and scattering based on particle composition (gas/aerosol/fog) in atmosphere

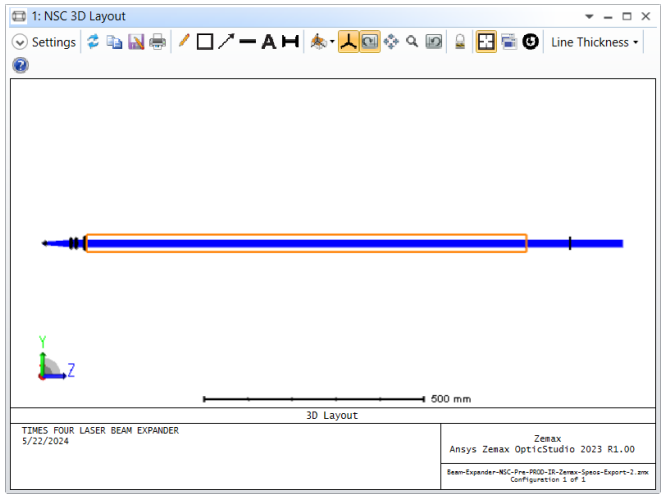


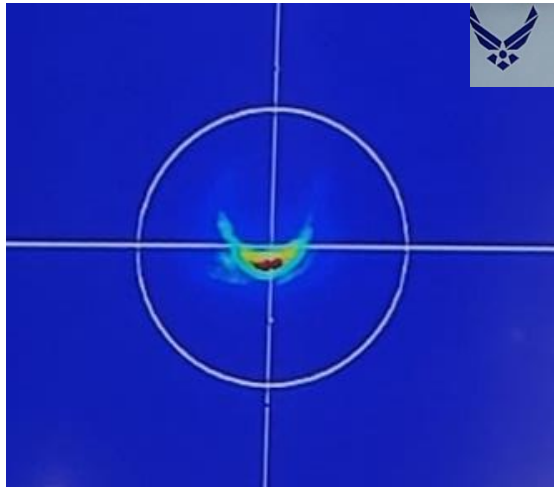


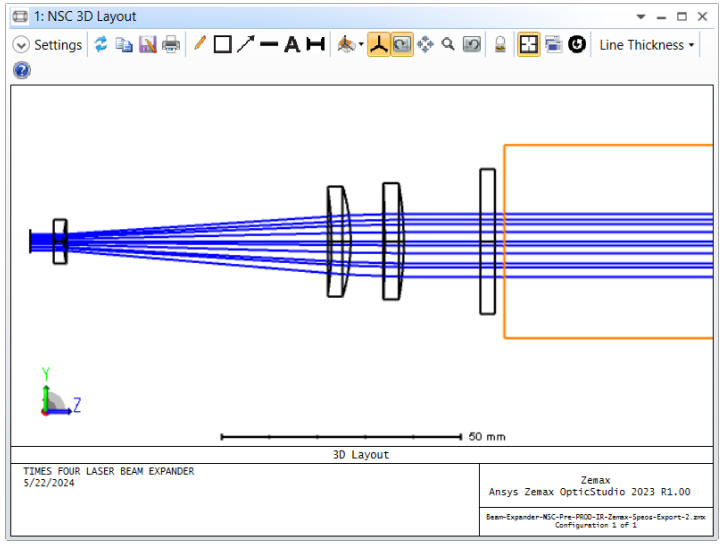
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Thermal Blooming









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Ablation

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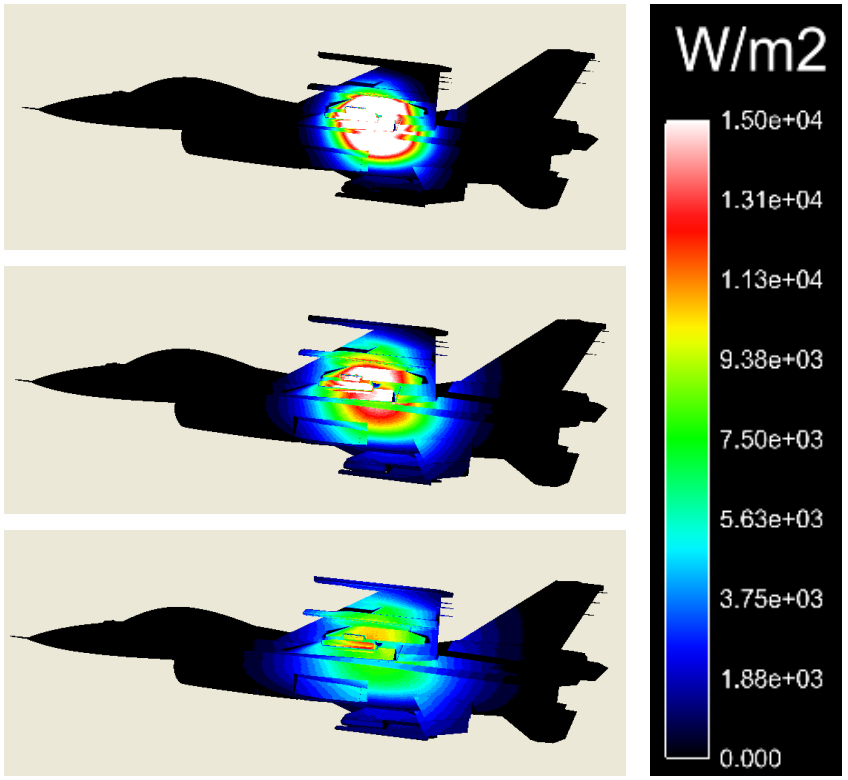
Target Impact: Irradiation, Heating, Melting and Solidification

Target Irradiation

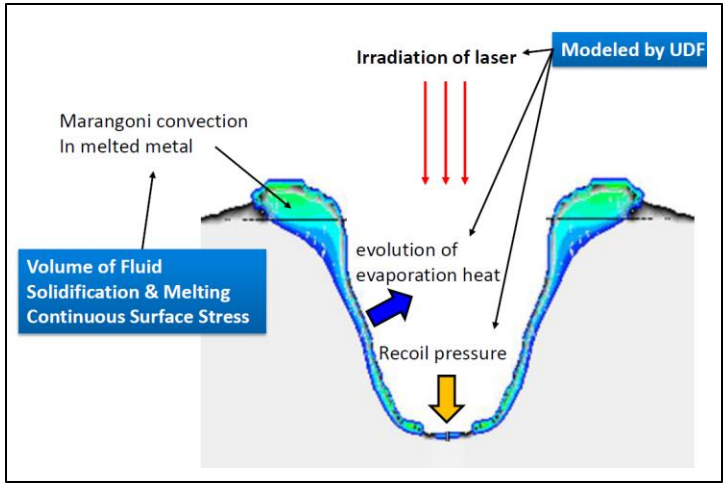
FWHM: 10°

FWHM: 15°

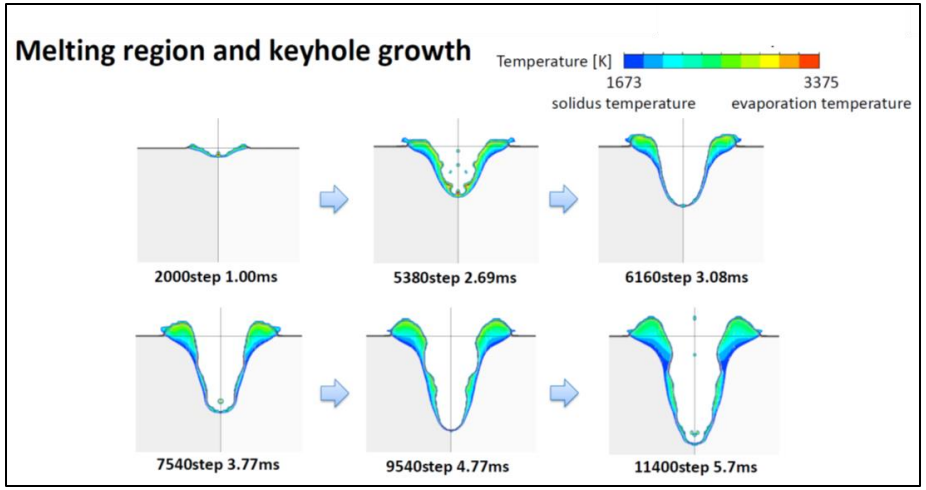
FWHM: 20°



Area	Shape	Center	Magnitude	Measure	Value	Rule	Test	Target
Body	Ellipse	(0 ; -3500 ; -10000)	irradiance	Maximum	57902.9 W/m2			
Left_Wing	Ellipse	(3000 ; -3500 ; -10000)	irradiance	Maximum	108708 W/m2			
Right_Wing	Ellipse	(-3000 ; -3500 ; -10000)	irradiance	Maximum	30709.3 W/m2			



CFD Simulation Method

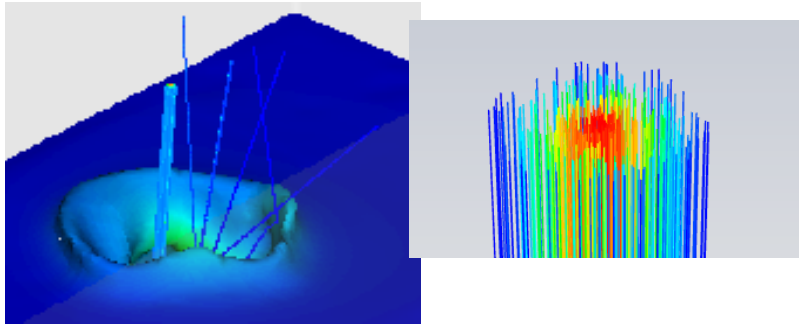


CFD Simulation Result

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Modeling laser impingement: DPM Ray Tracing

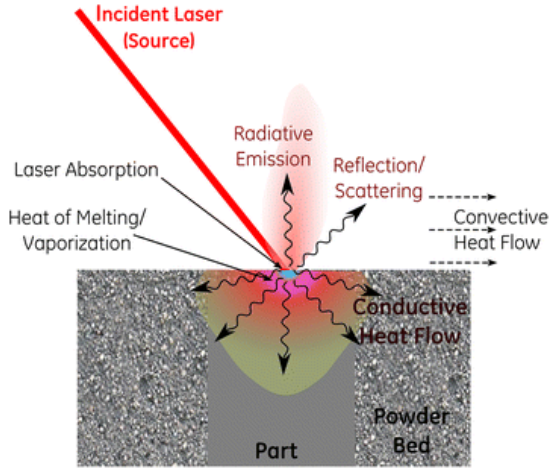
PBNS DPM with Eulerian Materials approach



Laser: DPM Ray Tracing model inside Fluent

Flow: Multi-species incompressible (can use Fluent)

Solid: Modeled with Eulerian Multiphase VOF solid/Liquid inside Fluent (CHT)

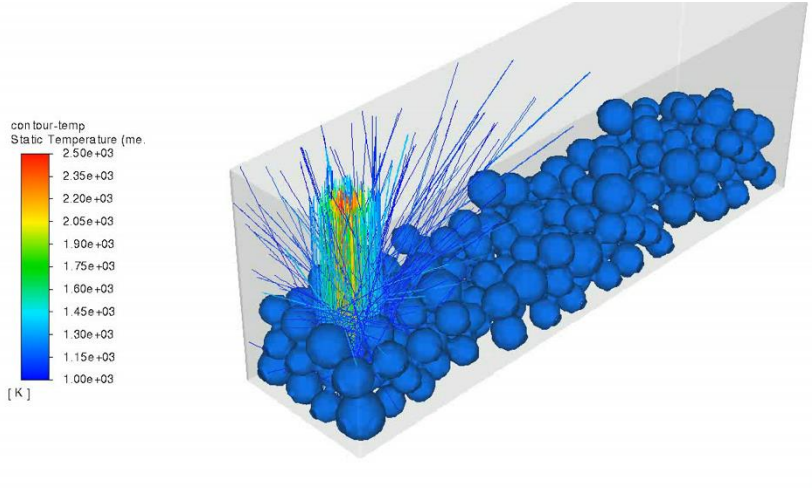


DPM Ray Tracing: Use built-in DPM model no drag/ forces. Define power Profile of laser matching normal Distribution
Limitations:
Surface shapes can be irregular, change shape, and state or updated during solution

Surface Facet Tracking: to deal with surface interaction and calculate vectors for reflection, absorption, surface change from other physics, Melting, sublimation, Oxidation.

Blowing effects: very accurate but will need extensive use of multi-phase Expressions/UDFs to describe phase change/mass transfer between phases: add mass, momentum, energy, species to gas phase

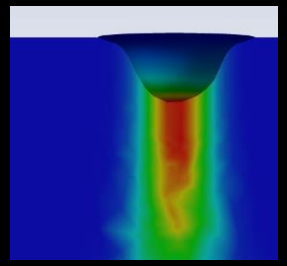
Limitations: Radiation from surface: Recoil, Gas absorption not represented. And other physics with structure of materials changes, etc.



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Modeling Laser Impingement on Solid Surface: Radiation

DBNS MDM approach



Laser: Monte Carlo or DO radiation model inside Fluent

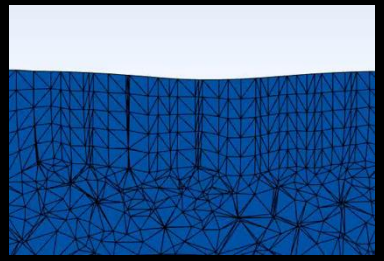
Flow: Multi-species compressible (can use Fluent)

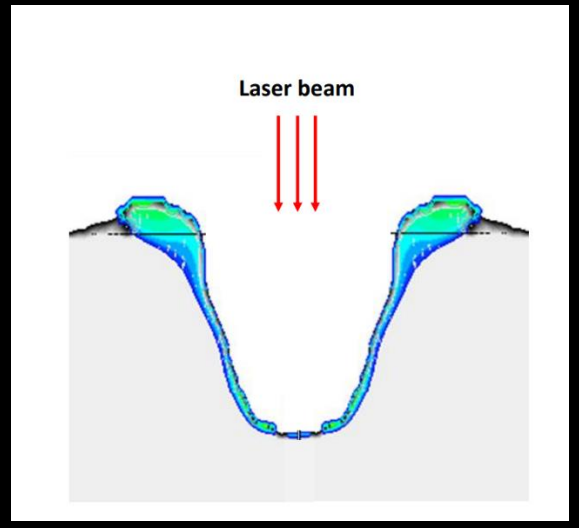
Solid: Can be modeled as a solid inside Fluent (CHT)

PBNS VOF approach

Surface recession: Use built-in ablation model (Vielle's law, surface reactions or erosion model UDF which allows customization of recession rate)
Limitations: No multi-phase

Blowing effects: possible at 2022R2 via mass-flux boundary or using UDF





Surface recession: Use built-in VOF model, with varying properties for the liquid part as a function of local conditions (T)
Limitations: surface effects on flow, eg friction etc?

Blowing effects: very accurate but will need extensive use of multi-phase Expressions/UDFs to describe phase change/mass transfer between phases: add mass, momentum, energy, species to gas phase

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Additional Optical Effects of Fluids

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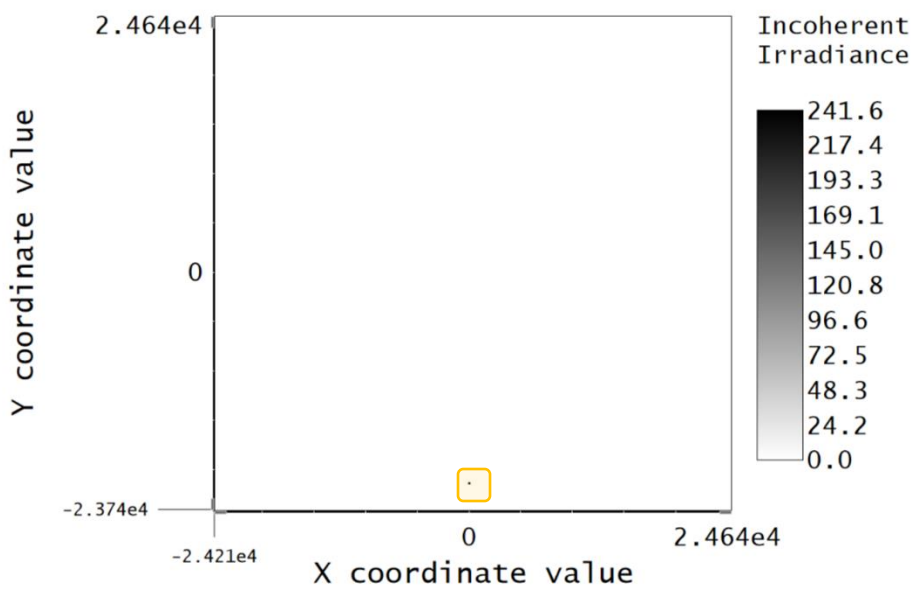
Plasma Mirror and Ablation Modeling

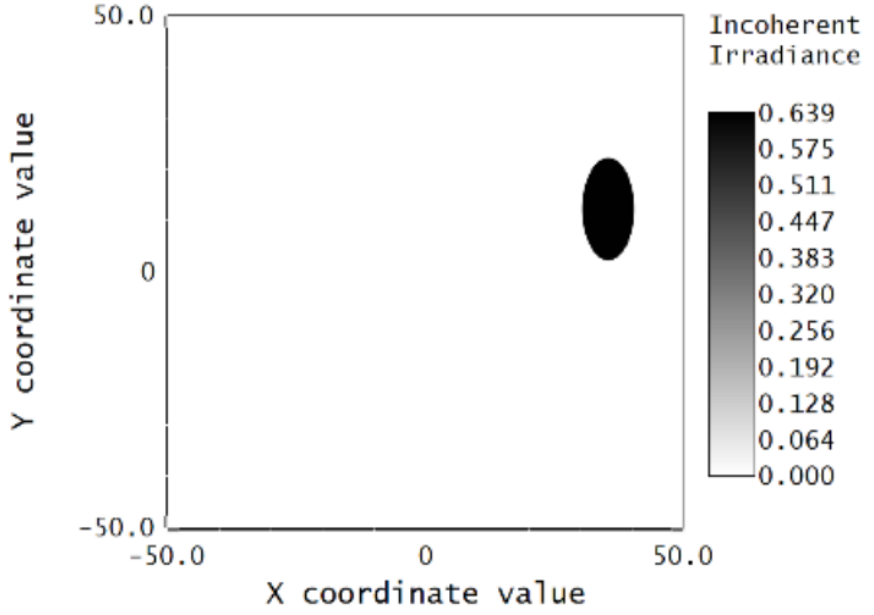
- Plasma mirror is not mirror in the traditional sense
  - Glass substrate such as fussed silica or other material
  - Some reusable systems use sacrificial layers on a substrate
  - The top layers a few atoms deep are vaporized

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Shift and Shape Changes

- Adding in tilt and various shapes of the voluemes with refractive index changes between layers, creates noticeable effects in the image position and distortion to the image.
- Various shapes and surfaces can be used to simulate strata effects



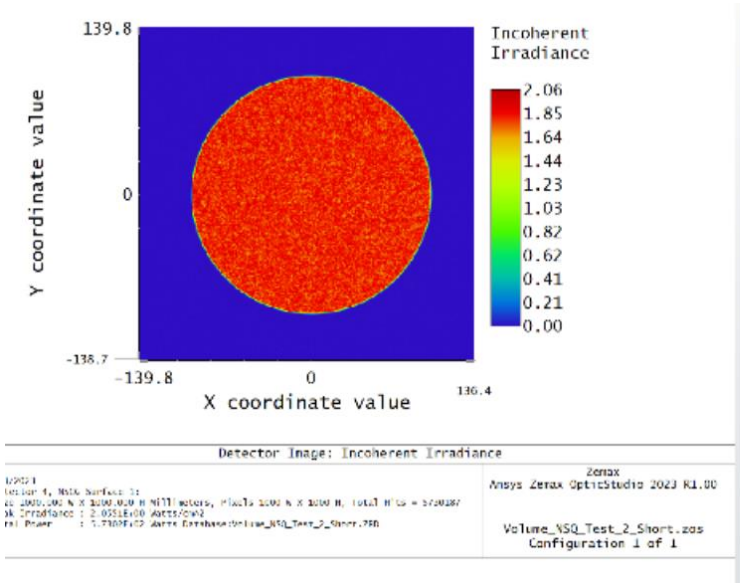


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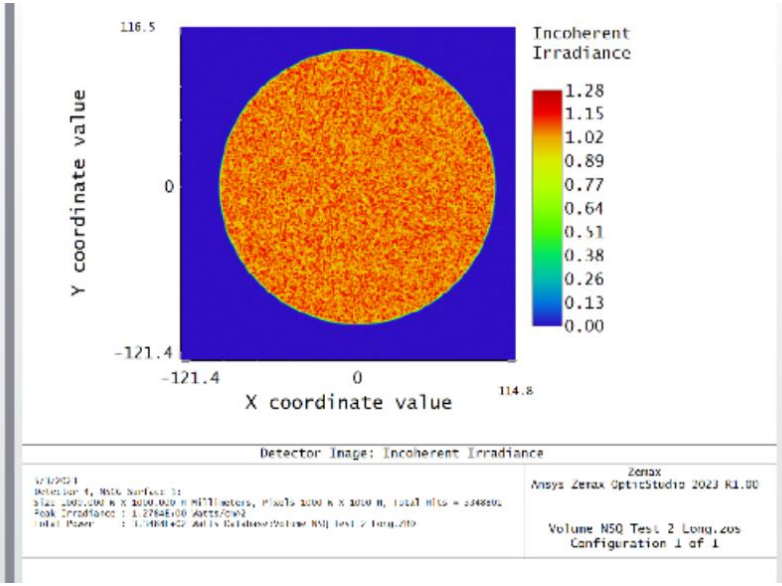
Intensity

- A combination of scattering and absorption creates a speckle pattern
- This speckled pattern intensities with distance

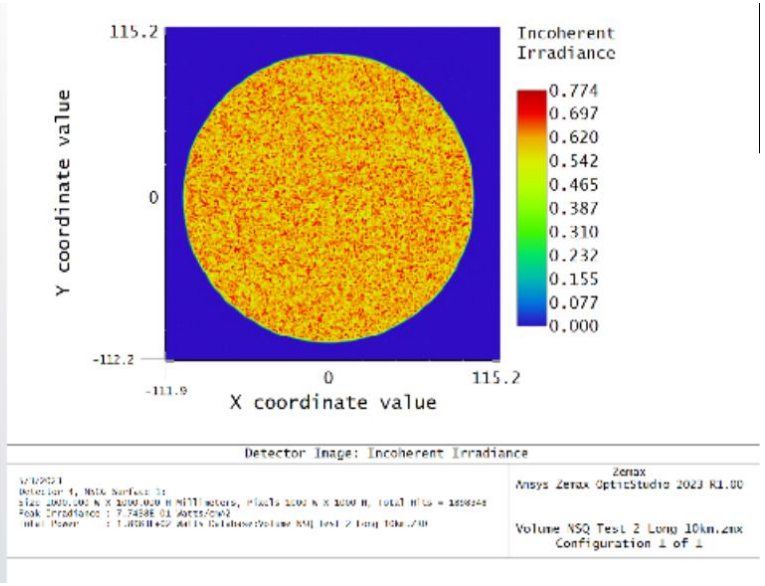
1 km



2 km



10 km

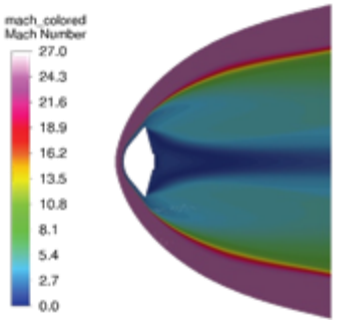


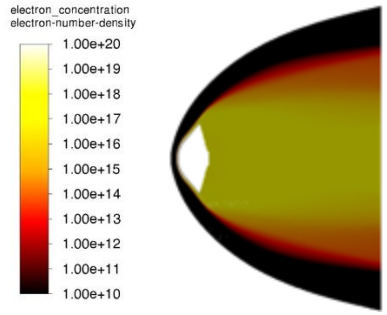
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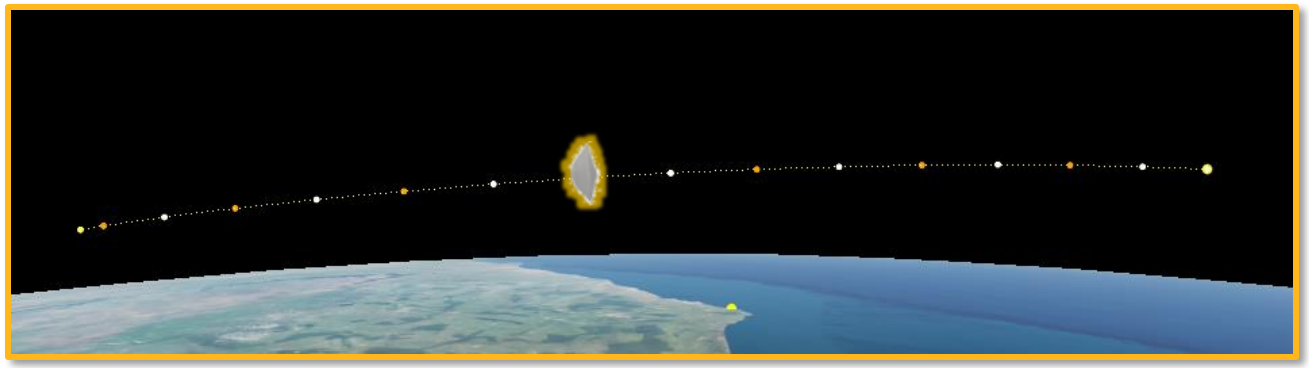
Data Presentation *(Spatially Varying Relative Permittivity)*

Altitude: *71.73 km*

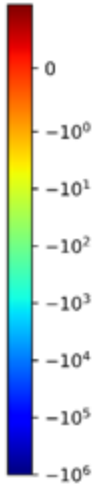
Mach: *23.89 (7049.20 m/s)*



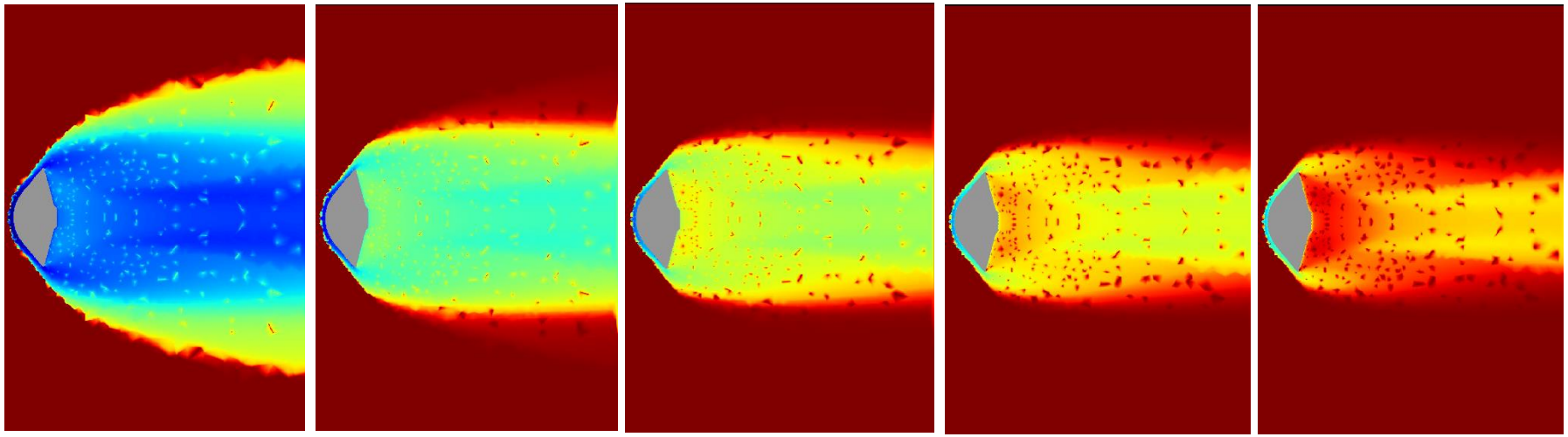




Relative Permittivity [-]



30 MHz *300 MHz* *1000 MHz* *1800 MHz* *3000 MHz*



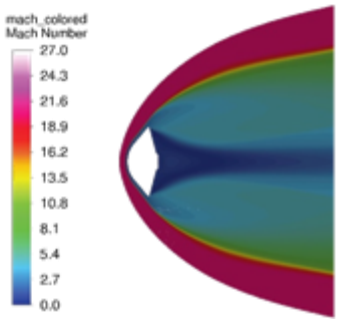
©2025 ANSYS, Inc.

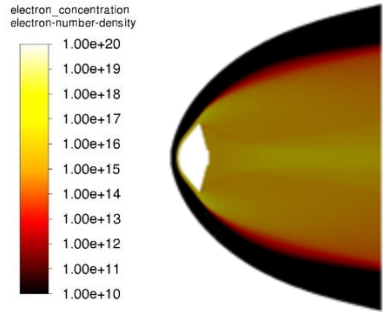
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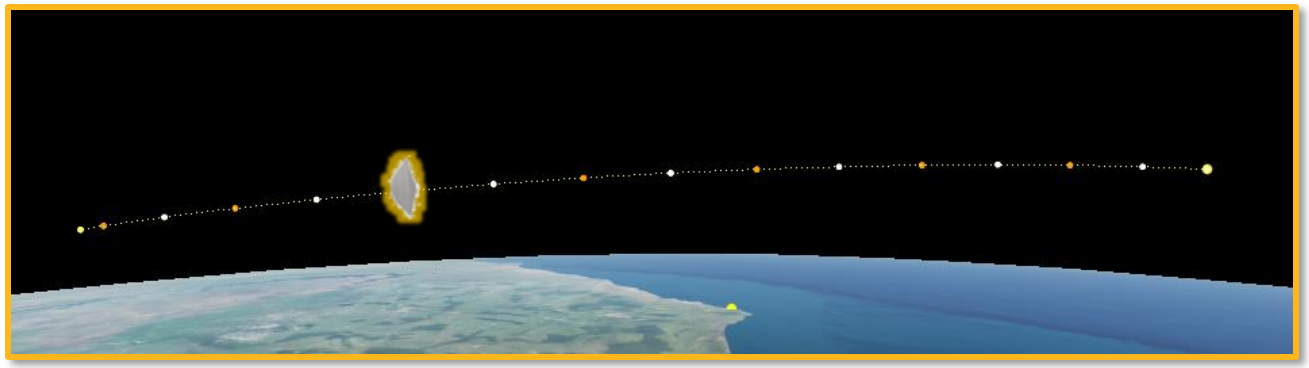
Data Presentation *(Spatially Varying Relative Permittivity)*

Altitude: *63.60 km*

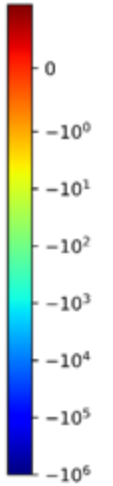
Mach: *20.09 (6223.40 m/s)*



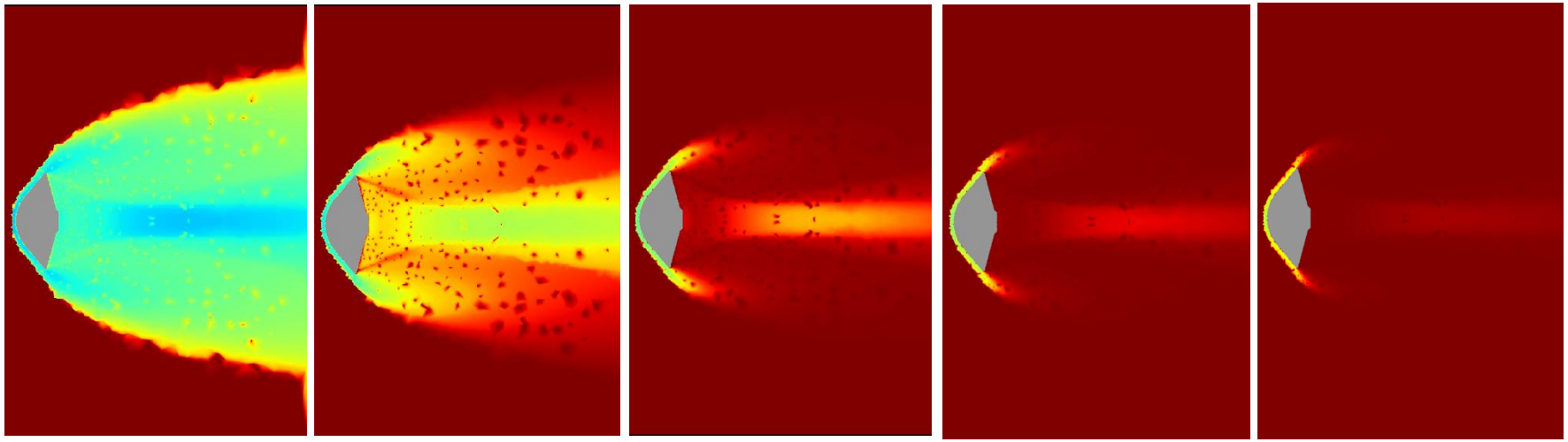




Relative Permittivity [-]



30 MHz *300 MHz* *1000 MHz* *1800 MHz* *3000 MHz*



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Special Thanks & References

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1. Kamel, M. S., Dragojlovic, Z., Viti, V., Mercado, F., Jia, R., La Cava S., "Aero-Optical Simulation in Ansys FLUENT; Application and Validation", AIAA-2024-1029, AIAA SciTech, Jan 8-12, 2024.
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Thank you!

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