

# TFAWS 2025 Inter II Session



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**THERMAL & FLUIDS  
ANALYSIS WORKSHOP**  
Ames Research Center 2025



## Characterization of Spacecraft Thruster Plumes via Augmented View Factor Methods for Spacecraft Docking Interactions

Presented by:

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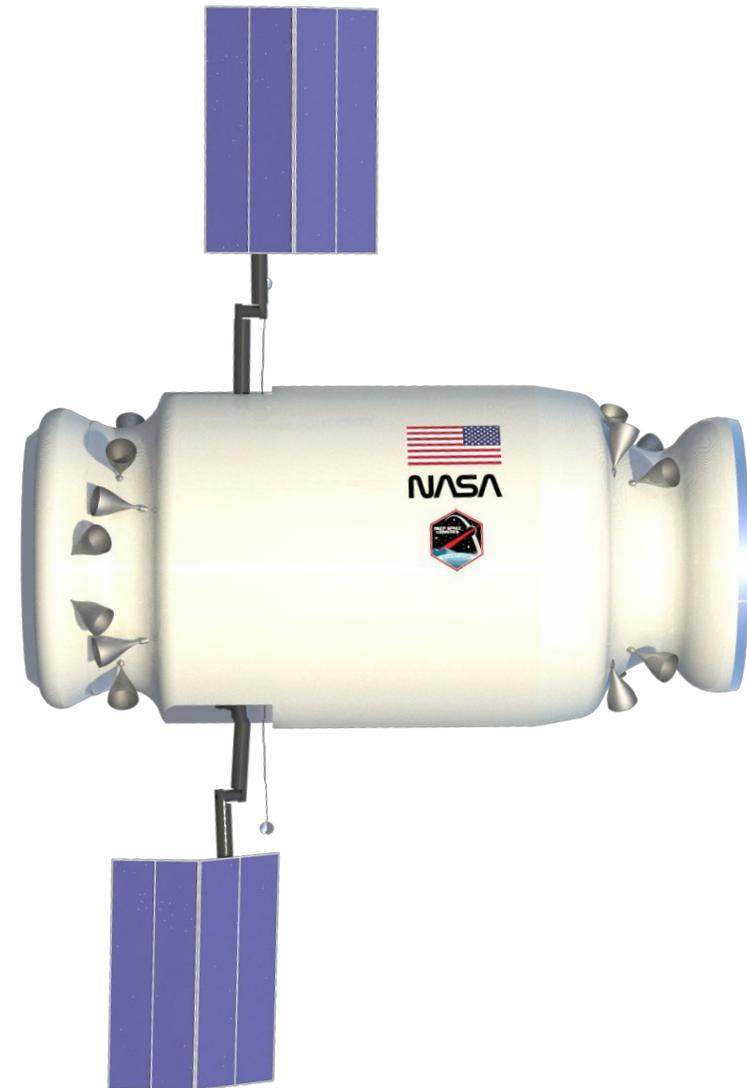
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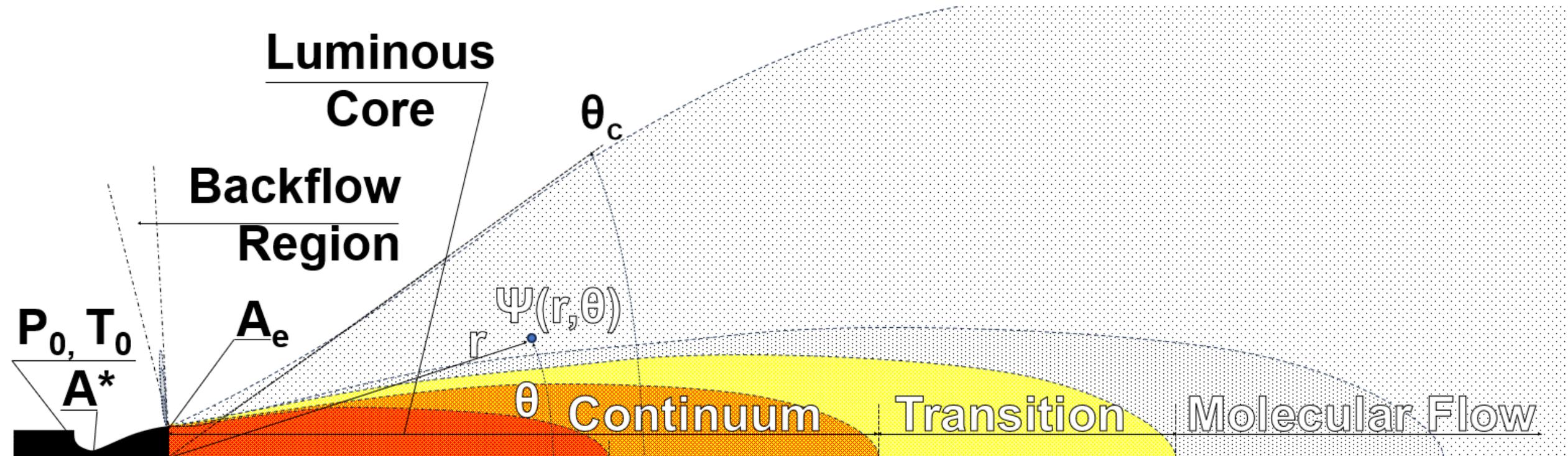


- **Background**
- **Motivation & Objective**
- **Methods**
- **Validation**
- **Simulation Results**
- **Conclusions & Future Work**

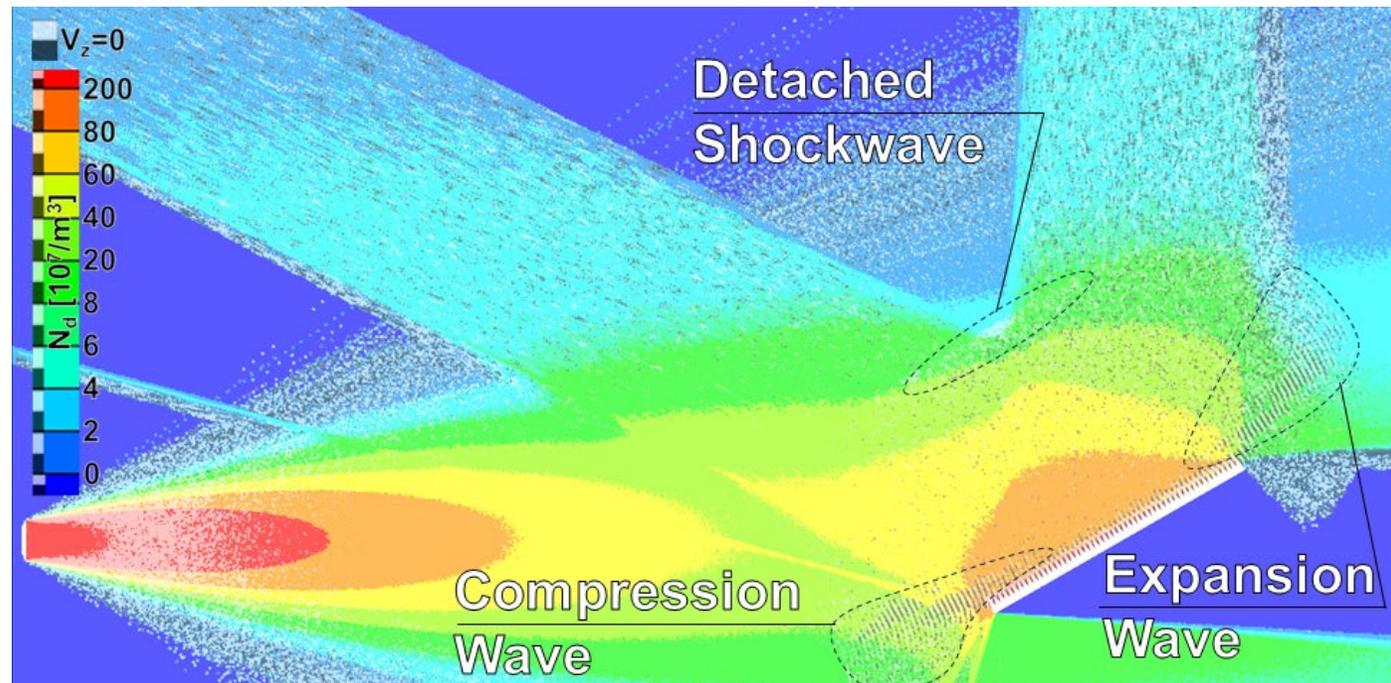


- **Spacecraft thruster plumes are multicomponent hypervelocity flows**

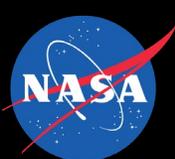
- At the nozzle exit there are flow properties based on stagnation conditions within the combustion chamber
- Plume breaks down into several distinct regions based on  $N_d$  (particle number density)
- Convenient to use an axisymmetric coordinate system  $(r, \theta)$  nozzle exit center to define points  $\Psi$  in field



- **Conventional plume modeling employs a Direct Simulation Monte Carlo (DSMC) method**
  - Ensembles of particles modeled to generate flow based on input characteristics
- **Provides intra- and inter- plume energy and momentum transfer characteristics**
- **Slow process**
  - Geometry models must be generated and validated (e.g. watertight)
  - Flow field mesh is then generated
  - Improperly resolved mesh/timestep can greatly underrepresent quantities

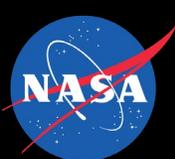


- **DSMC simulation enables the extraction of wavelike characteristics of hypervelocity flow**
  - Simulation shown over a textured inclined plate, showing number density  $N_d$  and velocity normal to the plane  $V_z$
  - Compression/expansion waves and detached shockwave are resolved by  $V_z$  sign inflections



- **Accuracy of a DSMC method is imperfect, the following are idealized**
  - Nucleation of solid particulate and droplet nucleation in the flow
  - Thruster nozzle residue discharge and thermal barrier coating ablation
  - Transients in static thruster firing, pulsed firing, thruster variability, and thruster lifetime variability
  - Mechanical damage due to hypervelocity impacts (ejecta creation) on impingement surfaces
  - Electrical potential of surfaces and plume are neglected, no arcing
  - Prop mass ratio variations due to pressure regulator limitations
  - Variable Hard Sphere and Soft Sphere (VHS/VSS) collision models obfuscate especially internal energy calculations
  - Wall interactions (catalysis/adsorption/desorption) rely on empirical data
- **Unrealistic to use DSMC to solve the 12 DOF orientation matrix between two spacecraft**
  - Cell size must be smaller than mean free path length
  - Single thruster plume sim for an environment volume of  $\sim 35 \text{ m}^3$  on a 64 thread Xenon takes  $> 48$  hours
    - Chemically frozen flow
- **Field of view analysis techniques, alternate to DSMC, are only qualitative**
- **Obtaining on orbit validation data of plume impingement is sparse (SPIFEX)**
- **Seeing the wavelike results of a DSMC sim illuminates ray tracing implementation potential**

**Develop a viewfactor based simulation technique, with shadowing, for spacecraft thruster plume impingement**



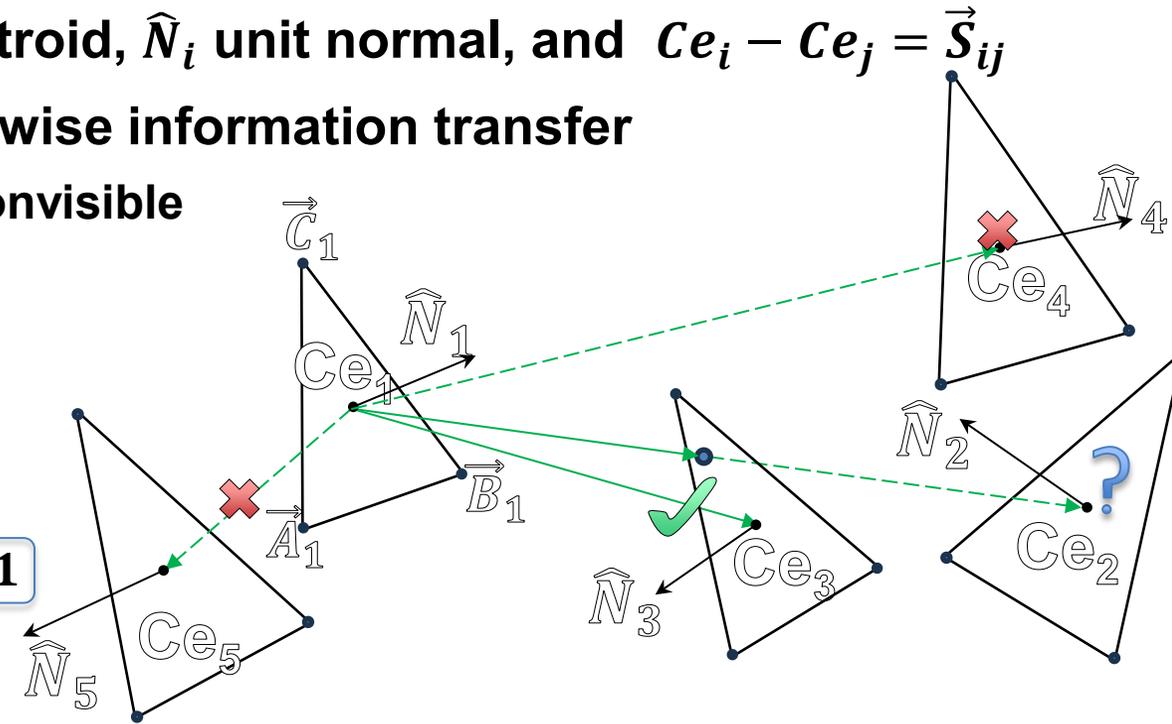
- **Element Selection**
- **What is a Viewfactor**
- **Simulation of an Unobstructed Plume**

- .STL files consisting of triangular facets are utilized as inputs, vertices  $\vec{A}_i, \vec{B}_i, \vec{C}_i$
- Basic vector quantities are computed:  $Ce_i$  centroid,  $\hat{N}_i$  unit normal, and  $Ce_i - Ce_j = \vec{S}_{ij}$
- Selection rule generated to determine elementwise information transfer
  - 1 implies elements may be visible, 0 implies nonvisible

Flagging the elements which are non-visible

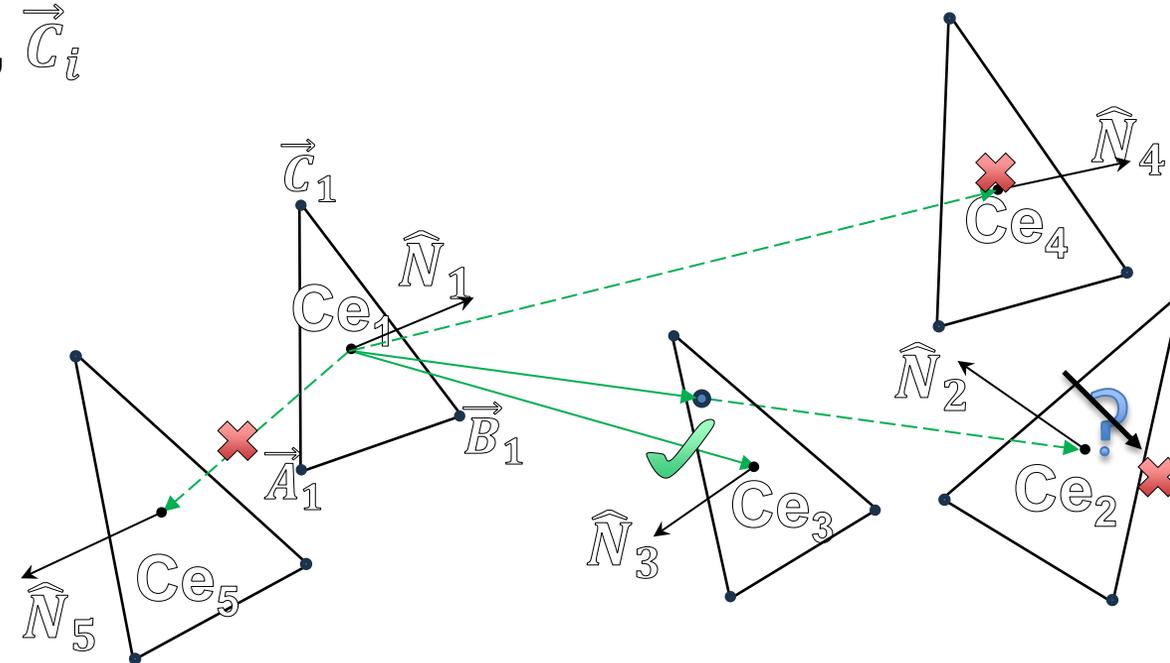
$$\left. \begin{array}{l} \hat{N}_i \cdot \hat{N}_j \approx 1 \\ \vec{S}_{ij} \cdot \hat{N}_j > 0 \\ \vec{S}_{ij} \cdot \hat{N}_i < 0 \end{array} \right\} \text{or } VFC_{ij} = 0$$

$$\left\{ \begin{array}{l} VFC_{1,1} = 0 \quad \hat{N}_1 \cdot \hat{N}_1 \approx 1 \\ VFC_{1,2} = 1 \\ VFC_{1,3} = 1 \\ VFC_{1,4} = 0 \quad \hat{N}_1 \cdot \hat{N}_4 \approx 1 \\ VFC_{1,5} = 0 \quad \vec{S}_{15} \cdot \hat{N}_5 < 0 \end{array} \right.$$



- Shadows are then applied to potentially visible elements based on triple product evaluation
- Conditions for  $s_k$  being bounded within  $\vec{A}_i, \vec{B}_i, \vec{C}_i$

$$\begin{aligned}
 & s_1 = \left\{ \begin{aligned} & (\vec{A}_j \times \vec{B}_j) \cdot \vec{S}_{i,jj} \\ & (\vec{B}_j \times \vec{C}_j) \cdot \vec{S}_{i,jj} \\ & (\vec{C}_j \times \vec{A}_j) \cdot \vec{S}_{i,jj} \end{aligned} \right. \text{ where } j \neq jj \\
 & - \left. \begin{aligned} & s_1 > 0 \wedge s_2 > 0 \wedge s_3 > 0 \\ & s_1 < 0 \wedge s_2 < 0 \wedge s_3 < 0 \end{aligned} \right\} \iff VFC_{ii jj} = 0 \\
 & - \left| \begin{aligned} & VFC_{1,2} = 0 \\ & VFC_{1,3} = 1 \end{aligned} \right.
 \end{aligned}$$



- Looped over both STLs in simulation
  - Vehicle self shadowing & target shadowing

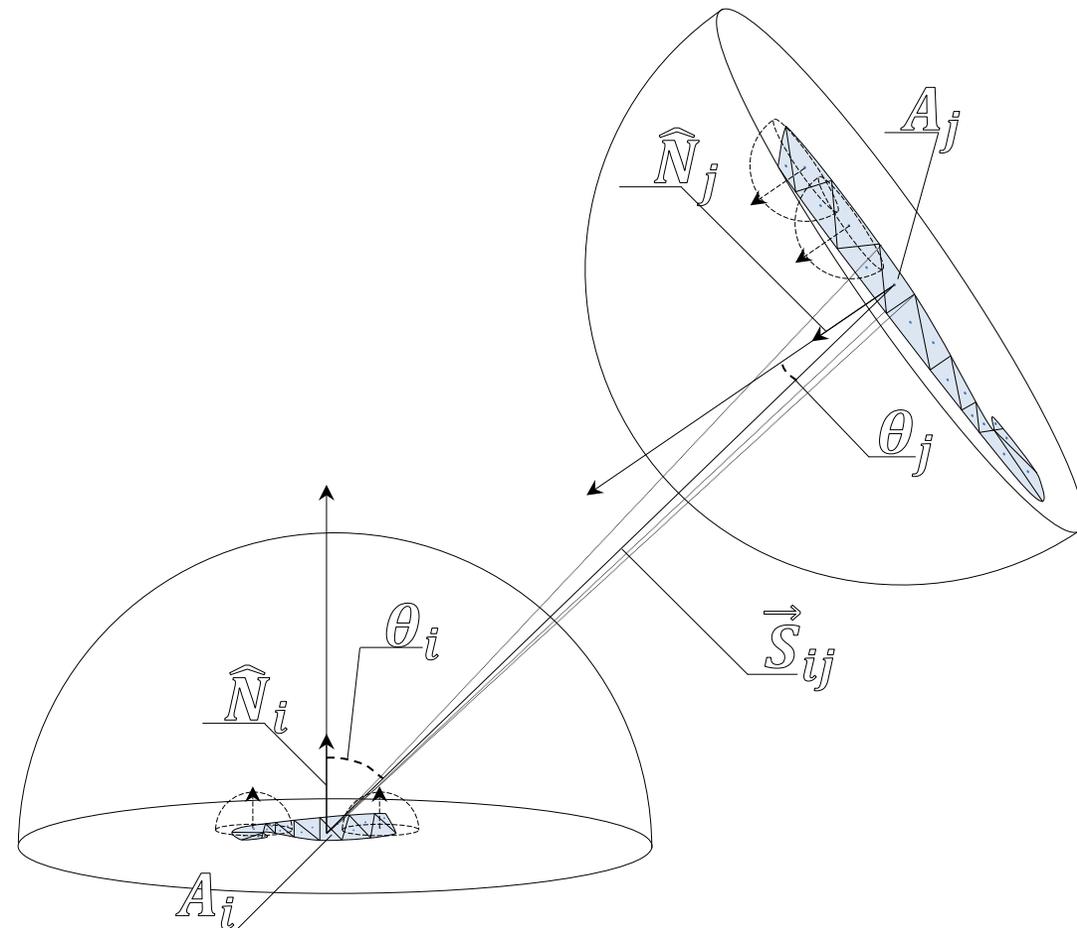
- **Viewfactor as adapted from radiative heat transfer is a means of quantifying projective area from a source differential area to a target differential area**

- STL Surfaces are discretized into constituent elements
- $i \rightarrow$  Thruster Exit Planes &  $j \rightarrow$  Target

$$VF_{ij} = \frac{\cos(\theta_i) \cdot \cos(\theta_j) \cdot A_i \cdot A_j}{\pi \cdot \vec{S}_{ij}^2}$$

$\vec{S}_{ij}$  - Distance between elements' centroids

$\hat{N}_{i \text{ or } j}$  - Element normal     $\theta_{i \text{ or } j}$  - Angle between normal &  $\vec{S}_{ij}$



- Test Case applied for co-axial disks ( $r_2=0.5\text{m}$ ,  $r_1=0.25\text{m}$ ) analytical model

$$VF_{1 \rightarrow 2} = 1/2 \cdot \left[ X - \sqrt{X^2 - 4 \cdot \left( R_2/R_1 \right)^2} \right] \text{ where } R_k = r_k/\Delta h \text{ \& } X = 1 + \frac{1+R_2^2}{R_1^2}$$

$\Delta h$ [m]	$VF_{1 \rightarrow 2}$ (Eq-Truth)	$VF_{1 \rightarrow 2}$ (Code)	[%Diff]
0.1	0.2467	0.1734	29.9
1.0	0.1172	0.1079	8.86
2	0.0481	0.0468	3.37
3	0.0244	0.0242	1.60
5	0.0096	0.0095	0.67
8	0.0038	0.0038	1.07
10	0.0025	0.0025	1.05
20	0.0006	0.0006	0.11

• Radiative heat transfer assumes  $\dot{q} = \iint_{A_i, A_j} V F_{ij} \cdot q'' dA_i dA_j$

• Assumed form for net force  $\mathbf{F} = \iint_{A_i, A_j} V F_{ij} \cdot P_t(r, \theta) \cdot \hat{N}_j dA_i dA_j$

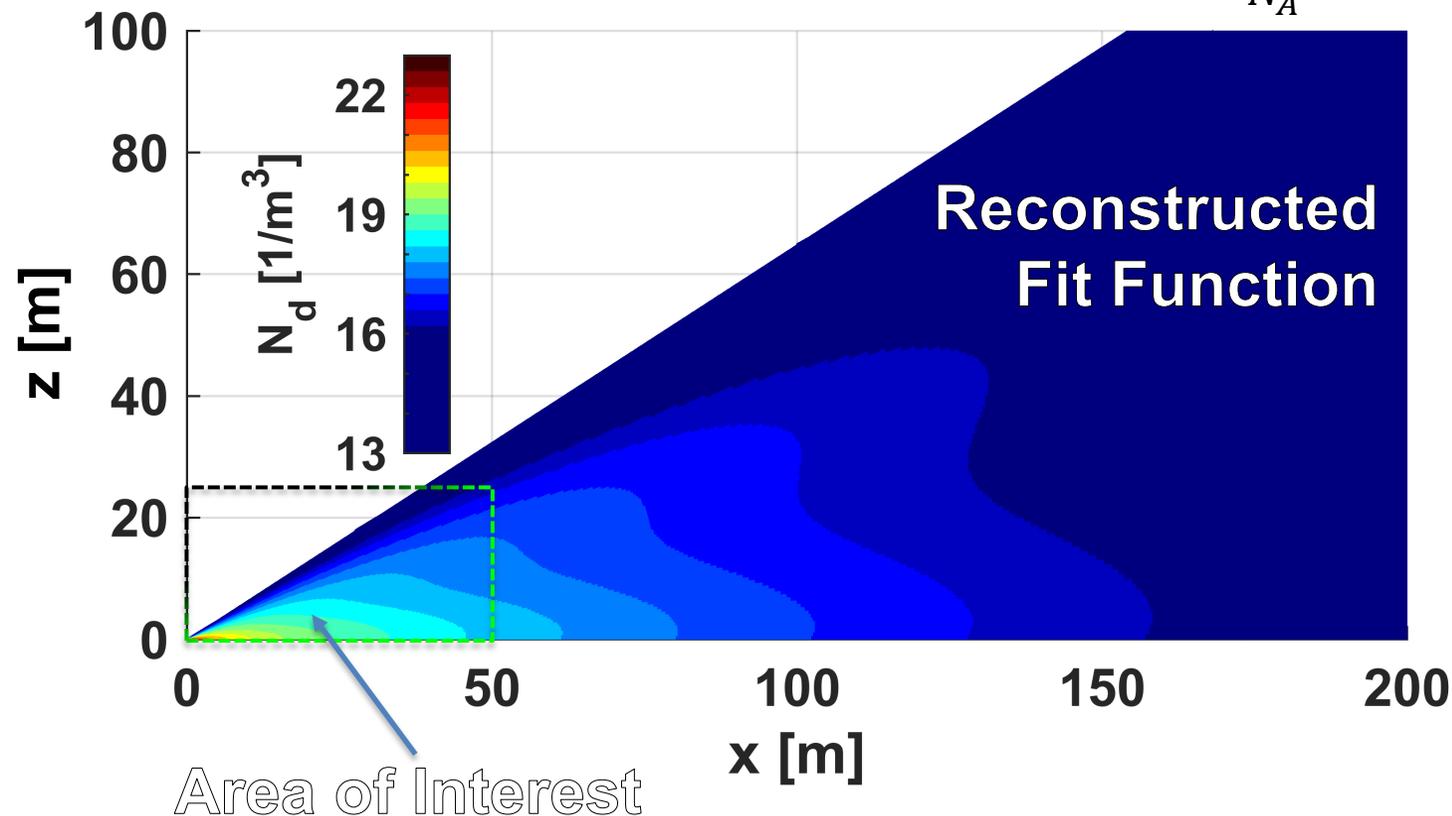
• DSMC simulation for thruster fit

1. Define 66 element thruster
2. Generate target to achieve ~100% force transfer
3. Define thruster: 400N – MMH/NTO @  $I_{sp} = 280s$  & Nozzle Exit Area
4. Iterate DSMC input deck (V, T, &  $N_d$ ) till convergence

• DSMC sim of empty plume field

- Apply ideal gas equation as necessary to get quantitative dataset (apply to  $N_d$ , T, U, etc.)

$$P_t(r, \theta) = P_s(r, \theta) + V_r(r, \theta)^2 \cdot N_d(r, \theta) \frac{M_w}{N_A}$$



- Validating the model requires generation of a dataset, employs previously modeled thruster

- Thruster placed at origin

- DSMC sims conducted: 2 → 50 m & 0 → 25 °**

- Target inclined about (0 0 0) within XZ plane

- No secondary rotation of target

- Sim time  $t_{sm} \approx 5 \cdot |\vec{s}| / (v_{thruster} \cdot \Delta t)$ ,  $\Delta t = 5 \mu s$

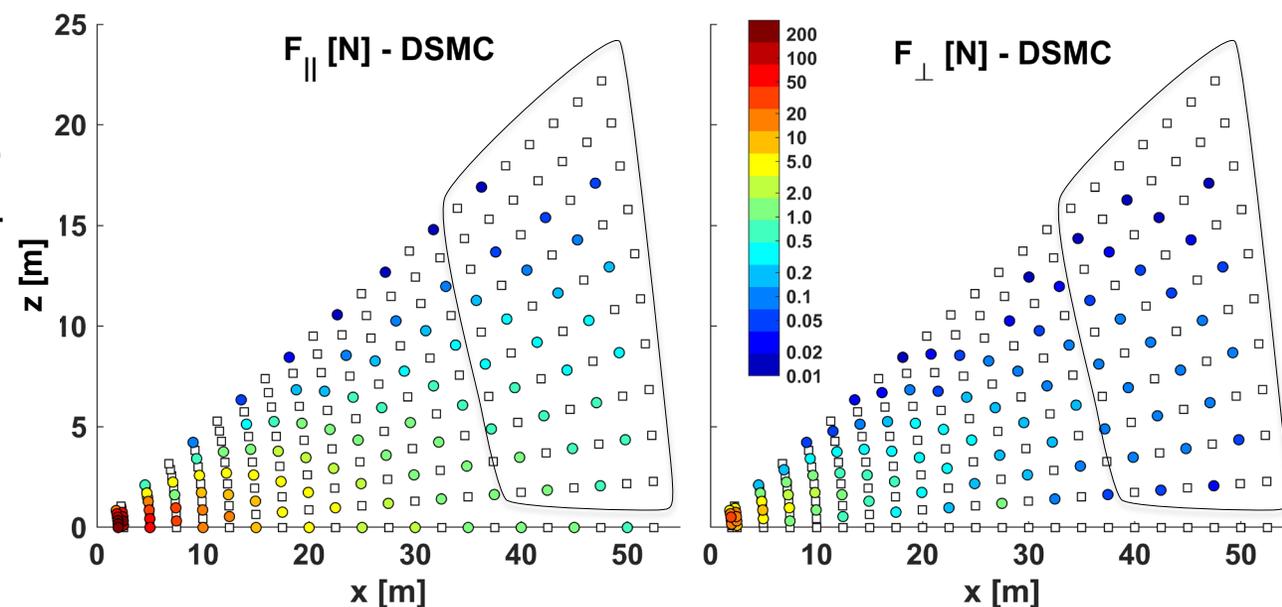
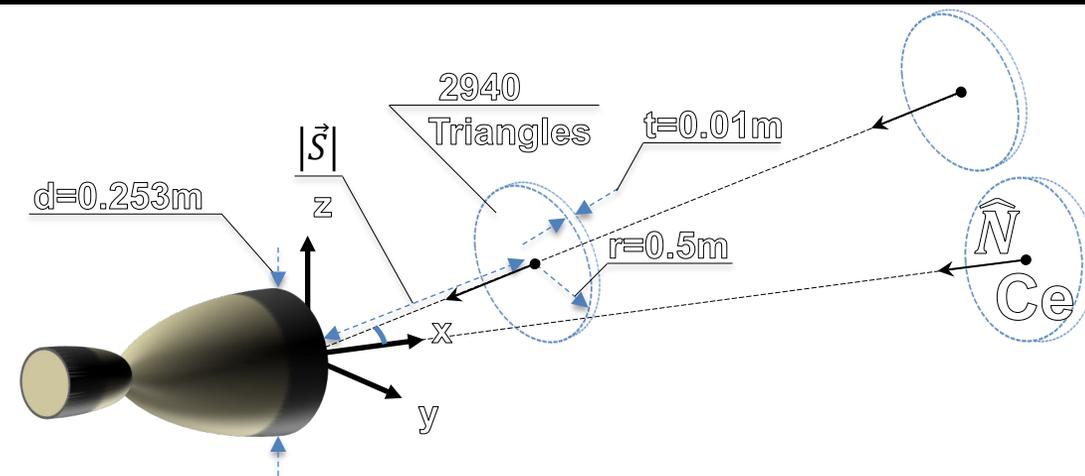
- Meshes discretized into  $l = 0.04m$  lengths

- Subdiscretized  $l/4$  global & near surface  $l/16$

- Ram limitations occurred, circled regions, subdiscretizations were reduced to  $l/3$  to enable completion (512GB RAM limited)

- Net forces encompass >4 orders magnitude over the probed range**

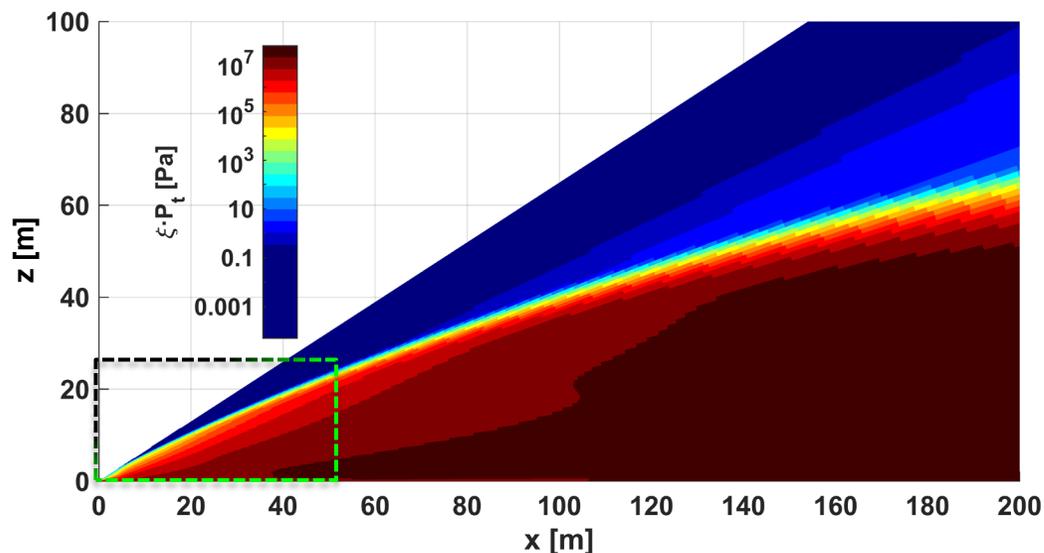
- White squares indicate no data at that point



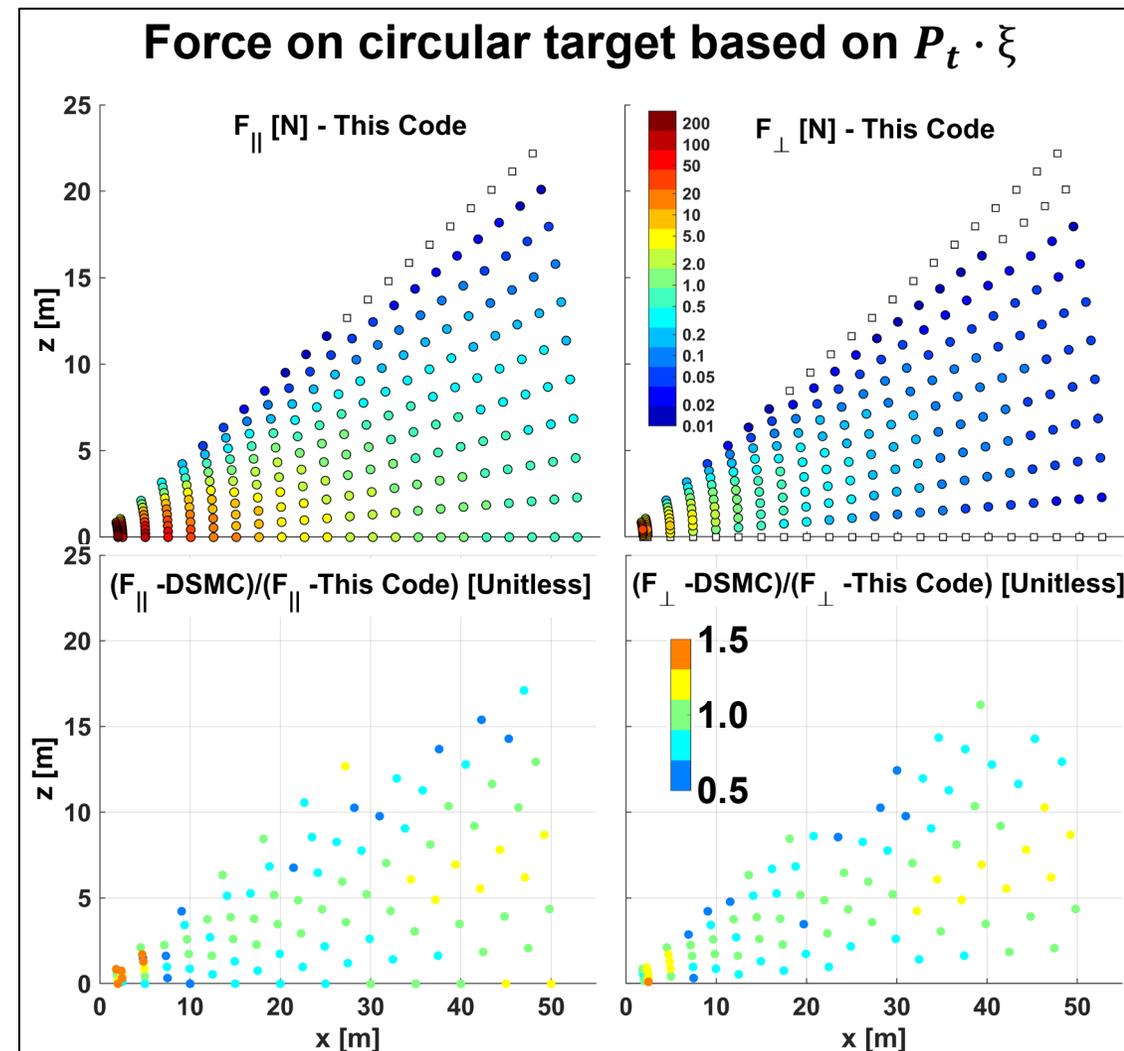
- Using  $P_t(r_j, \theta_j)$  as previously obtained
- Combine terms

$$F = \iint_{A_i, A_j} V F_{ij} \cdot P_t(r_j, \theta_j) \cdot \xi(r_j, \theta_j) \cdot \hat{N}_j dA_i dA_j$$

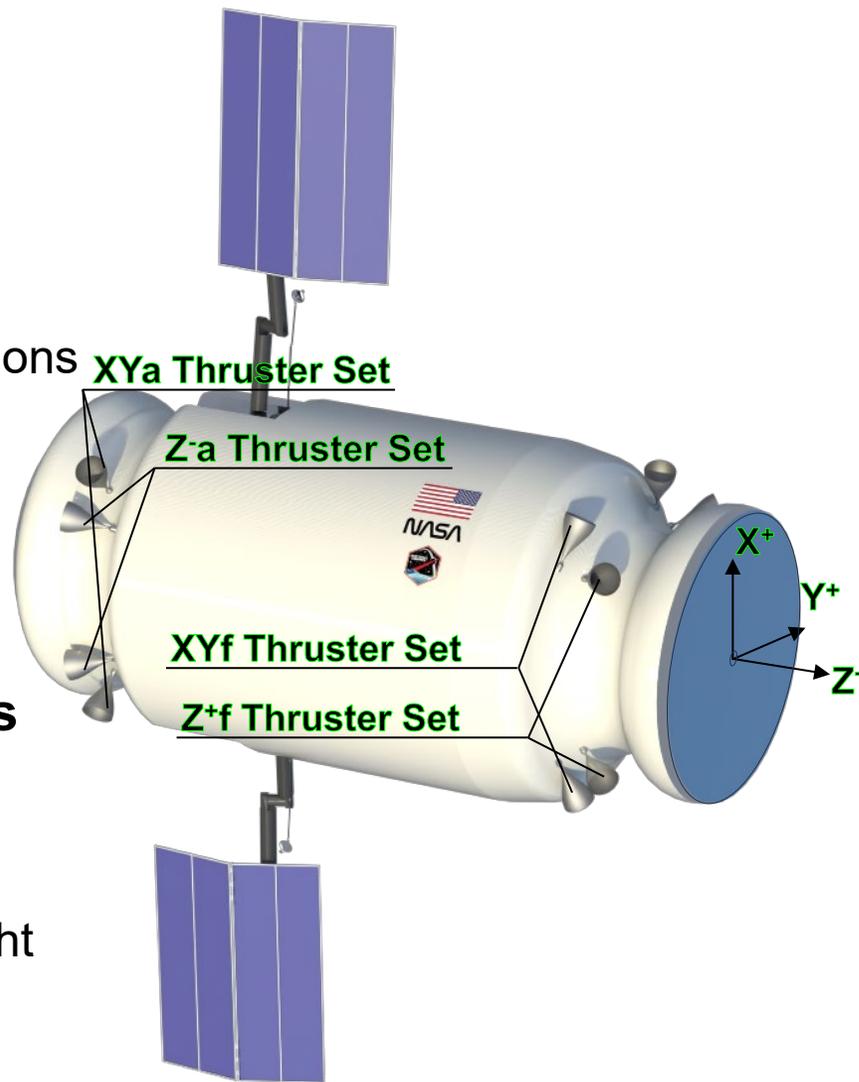
- Additional terms incorporated into the plume calculation  $\xi(r_j, \theta_j)$  to match DSMC simulations of the circular target



- Circular target acts as a convolution operation on the aggregate values of local pressure
- Accurate, >4 order magnitude range of forces

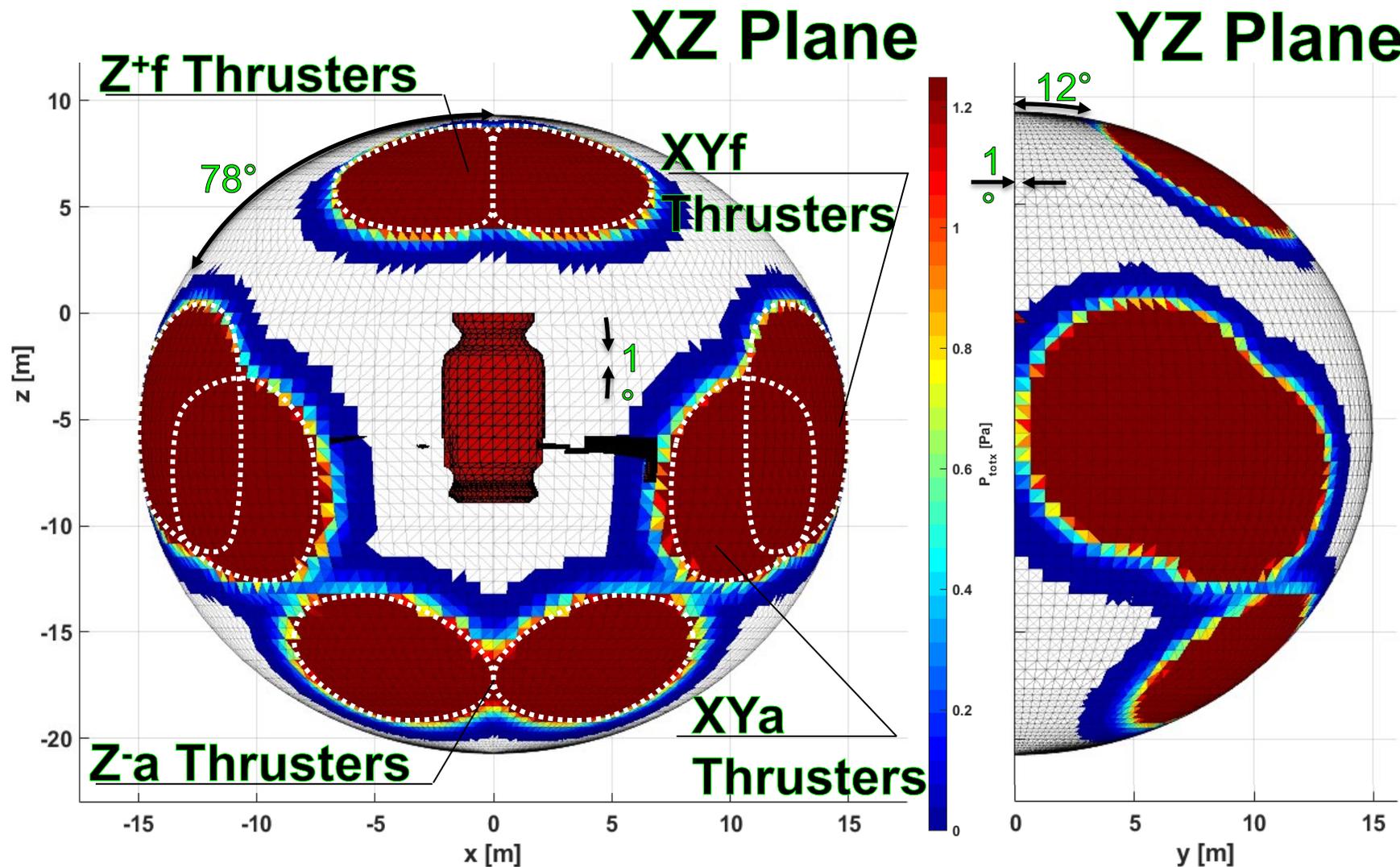


- **Compatible with common launch platforms**
- **16 Thrusters**
  - 8 Aft “a” and 8 Forward “f”
  - $Z^{\pm}$  and XY primary orientations
  - Docking port on  $Z^+$  face
- **Thruster sets enable high maneuverability & control about center of mass**
- **$X^{\pm}$  Solar Arrays & Antennas**
  - Gimbaled
- **16,000 kg mass**
  - Payload + Prop + Dry Weight
  - 6,000kg Payload
- **Lots of  $\Delta V$**



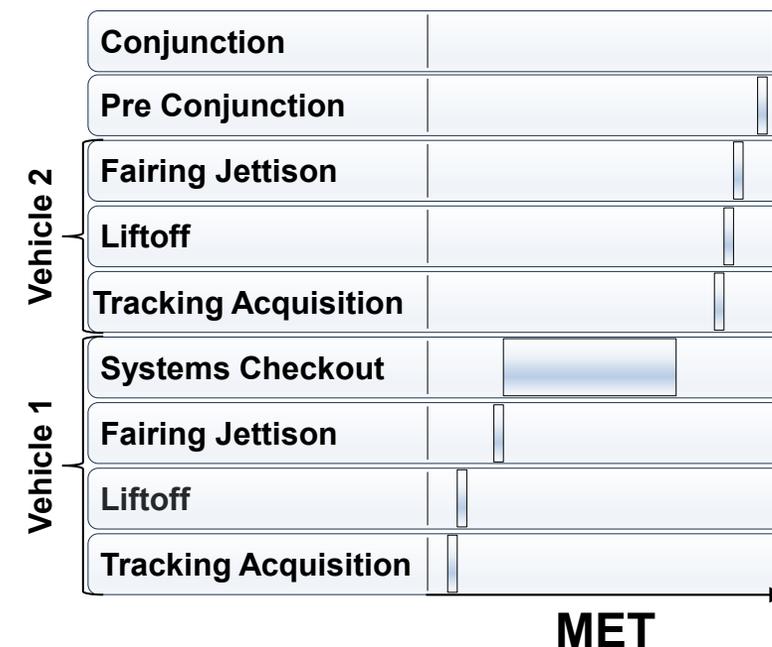
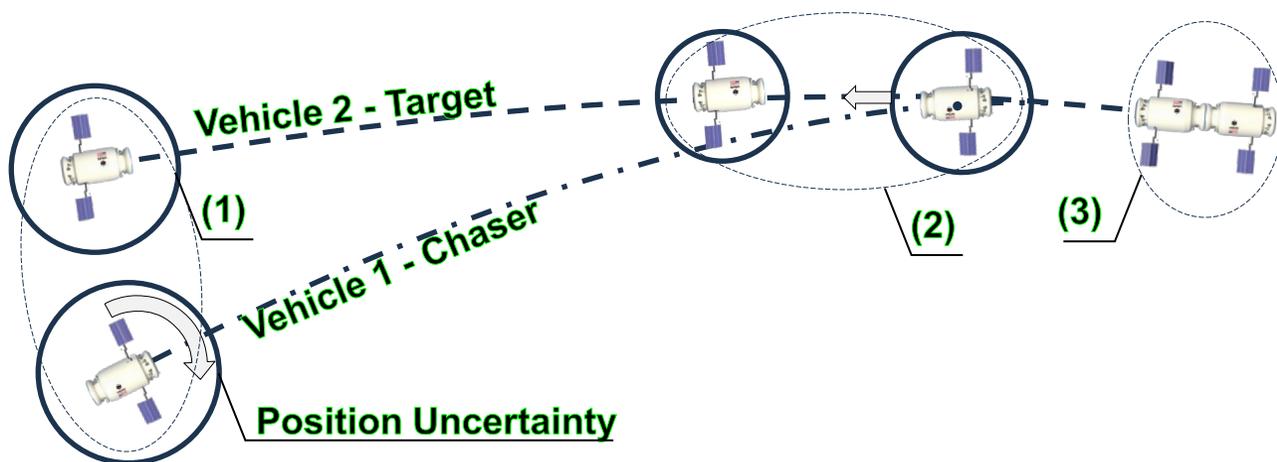
Thruster	X	Y	Z
Z+f Y+ X+	-0.3008	0.6057	0.7366
Z+f Y- X+	-0.3008	-0.6057	0.7366
Z+f Y- X-	0.3008	-0.6057	0.7366
Z+f Y+ X-	0.3008	0.6057	0.7366
XYf Y+ X+	0.8911	0.3720	-0.2600
XYf Y- X+	0.8911	-0.3720	-0.2600
XYf Y- X-	-0.8911	-0.3720	-0.2600
XYf Y+ X-	-0.8911	0.3720	-0.2600
Z-a Y+ X+	0.3008	0.6057	-0.7366
Z-a Y- X+	0.3008	-0.6057	-0.7366
Z-a Y- X-	-0.3008	-0.6057	-0.7366
Z-a Y+ X-	-0.3008	0.6057	-0.7366
XYa Y+ X+	0.7481	0.6611	-0.0580
XYa Y- X+	0.7481	-0.6611	-0.0580
XYa Y- X-	-0.7481	-0.6611	-0.0580
XYa Y+ X-	-0.7481	0.6611	-0.0580

- Sphere placed around vehicle centroid
  - Sphere normals oriented toward vehicle
  - $1^\circ$  arc length along triangular facet legs
- Dotted regions on XZ plane are per thruster impingement
- Fast dimensional analysis
  - Hold target vehicle within an elliptic cone defined by  $78^\circ$  from azimuth along major and  $12^\circ$  from azimuth along minor axes the  $Z^+f$  thrusters has negligible plume impact
    - Soft GNC constraint
- Enables by angle “yes/no” with confirmed visual

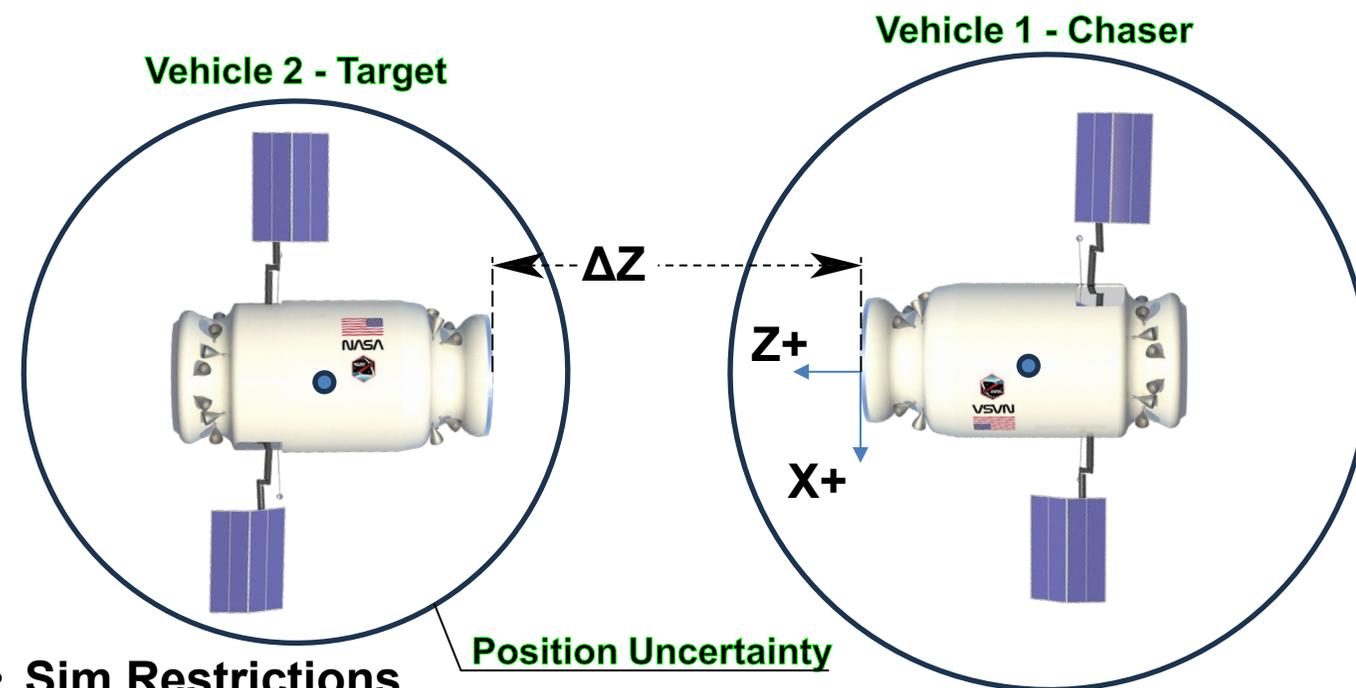




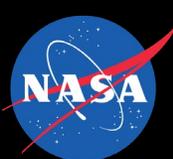
- 48° Inclination @ 165 km circular orbit
- Range safety gave blessing for prograde launch from West Coast



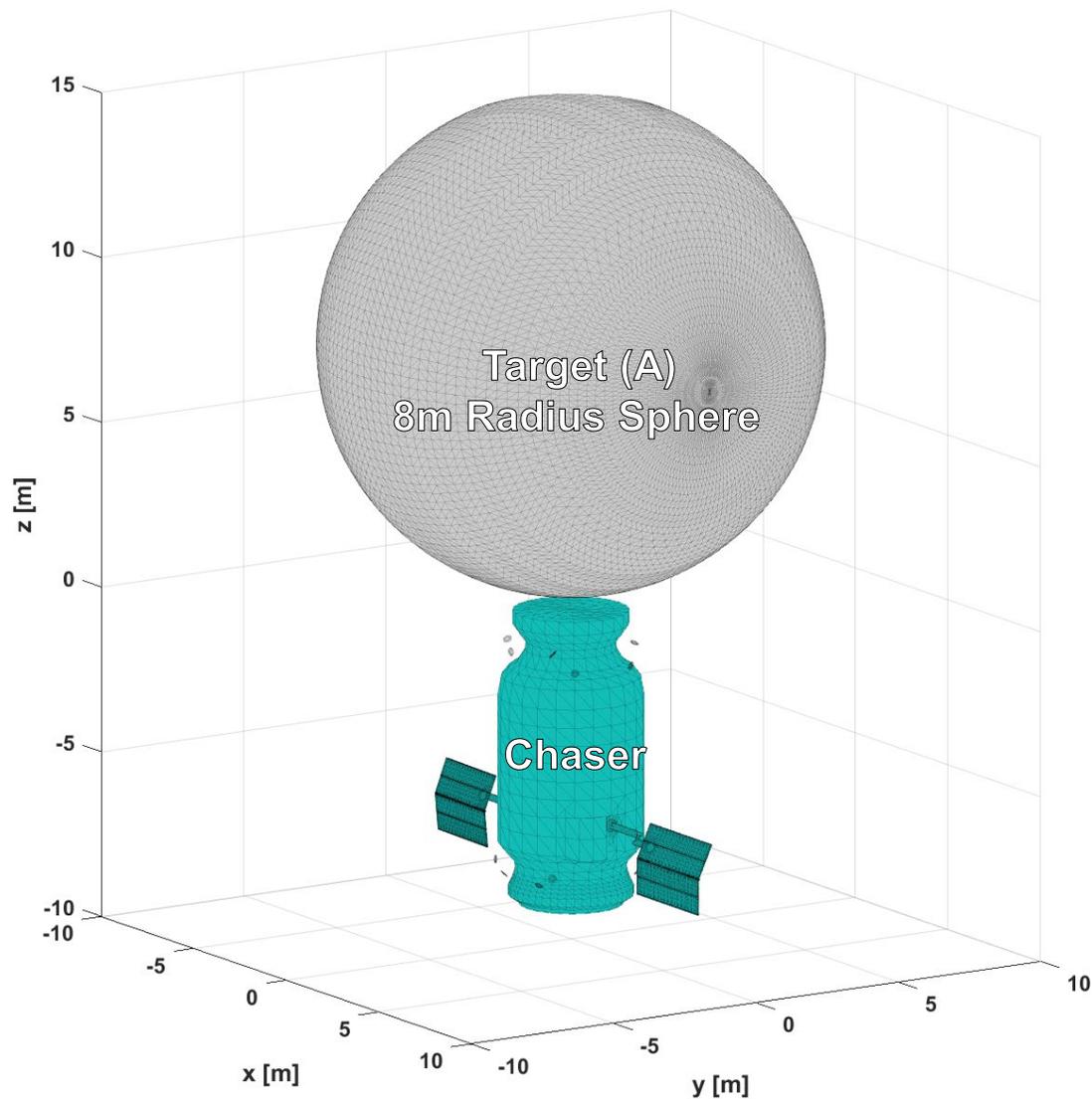
- **From thruster orientation analysis**
  - No self impingement for reference solar array & antenna position
- **Error of Target is smaller than Chaser**
- **Obtain worst on worst scenario**
  - Apply spherical body to represent error tracking  $\delta$  for both vehicles through target vehicle spherical representation
  - Search for any inflections, instabilities, & reversals of plume effects as functions of  $\Delta x$ ,  $\Delta y$ ,  $\Delta z$  &  $\alpha$ ,  $\beta$ ,  $\gamma$  for chase vehicle



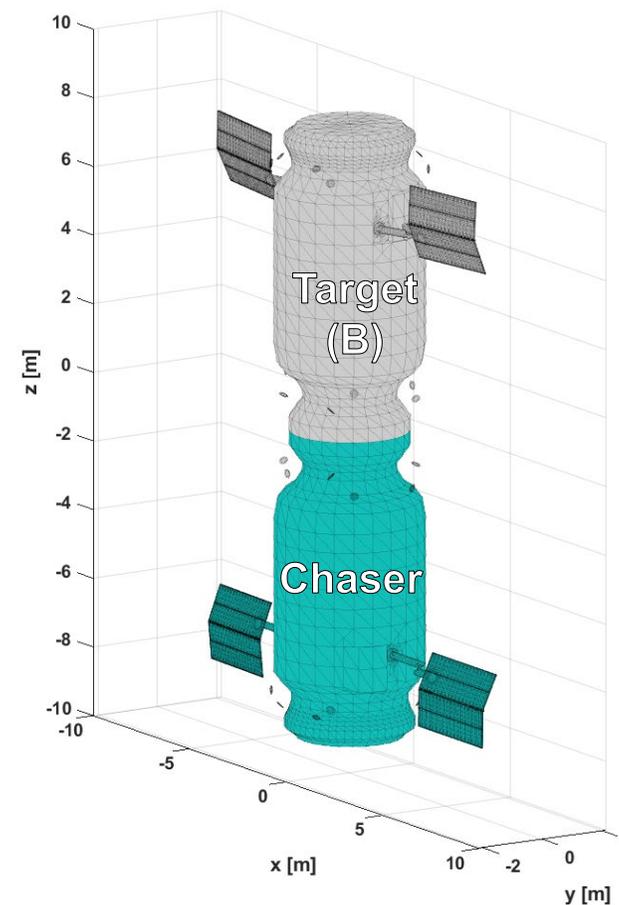
- **Sim Restrictions**
  - Assumes static thruster firing
  - No displacement of vehicles due to plume
    - Separate model to handle kinematics
  - Reflections & shear effects neglected
  - No modeled panel deflection



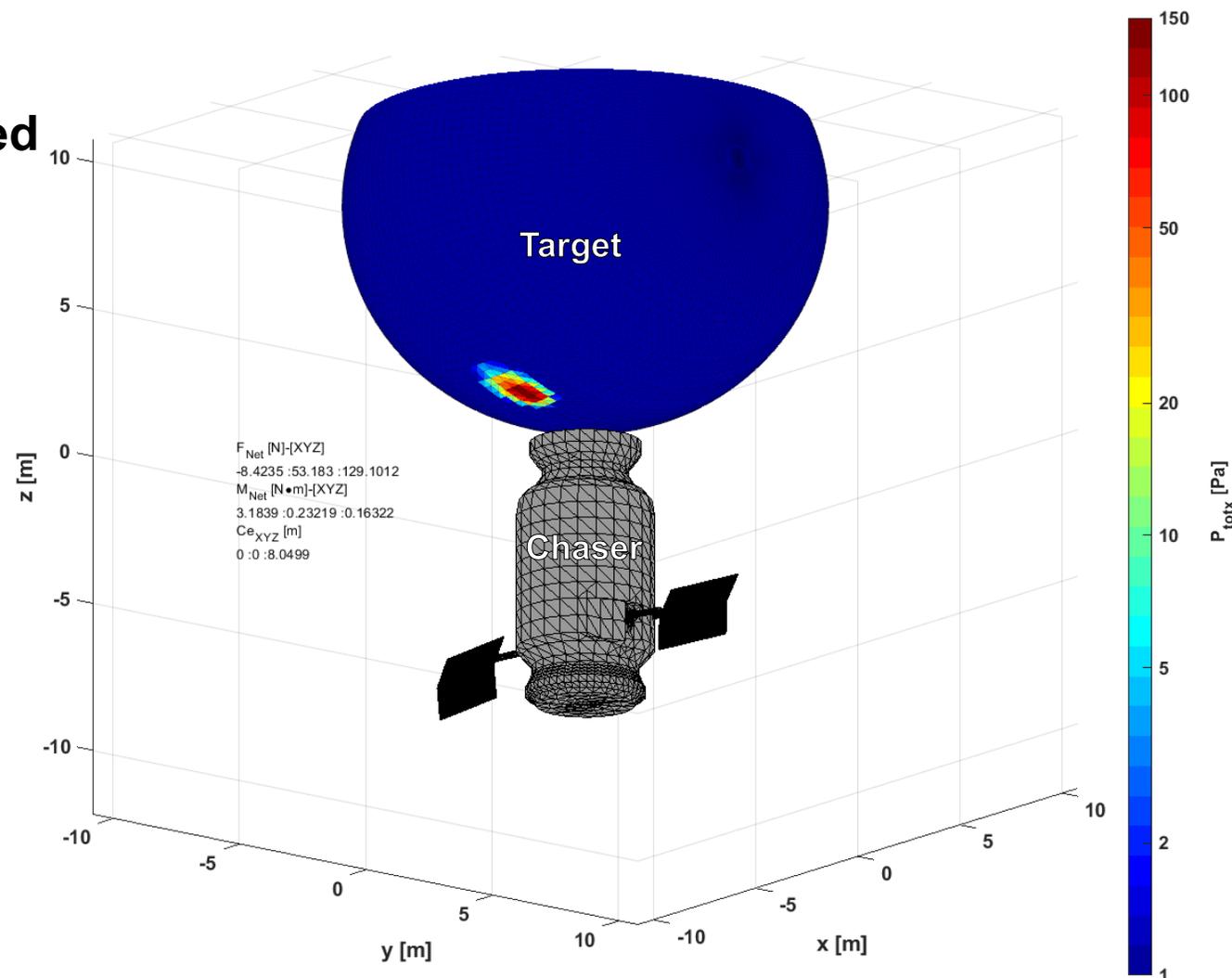
# Application of Simulation: Analysis Configurations



$$(\Delta x = \Delta y) = 0$$



- During preliminary planning phases rendezvous objects may be unknown, need-to-know, undefined, or unidentified
  - Change the sphere size to represent different objects
  - (e.g. Moon – ground plume interaction)
- Use a Sphere as general geometry
  - Enables projections onto a 2d plane at distance
  - Good for docking craft with moveable appendages: radiators, solar arrays, *etc.*
  - Enables objects to be placed inside the sphere, anything highlighted is in plume

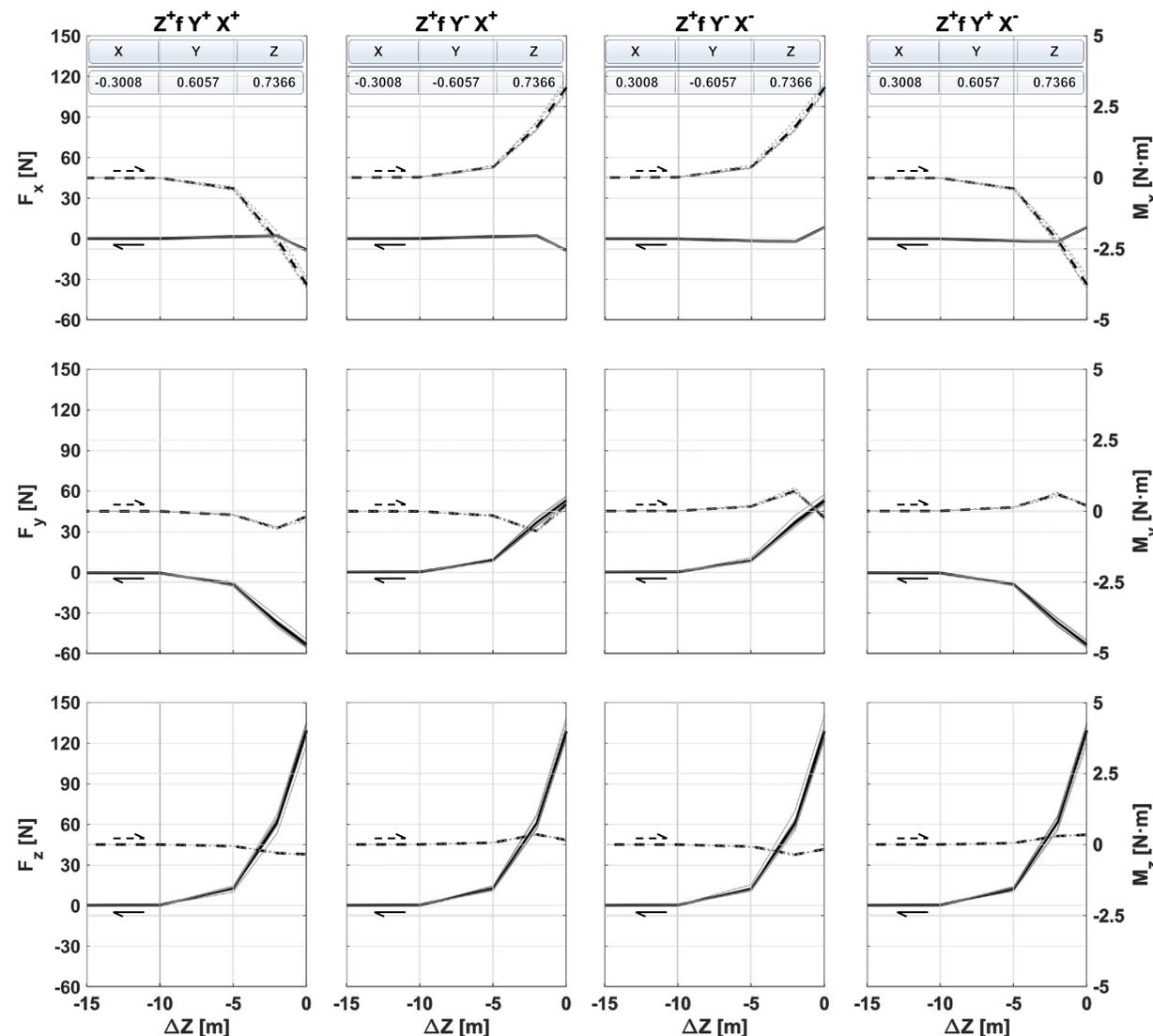




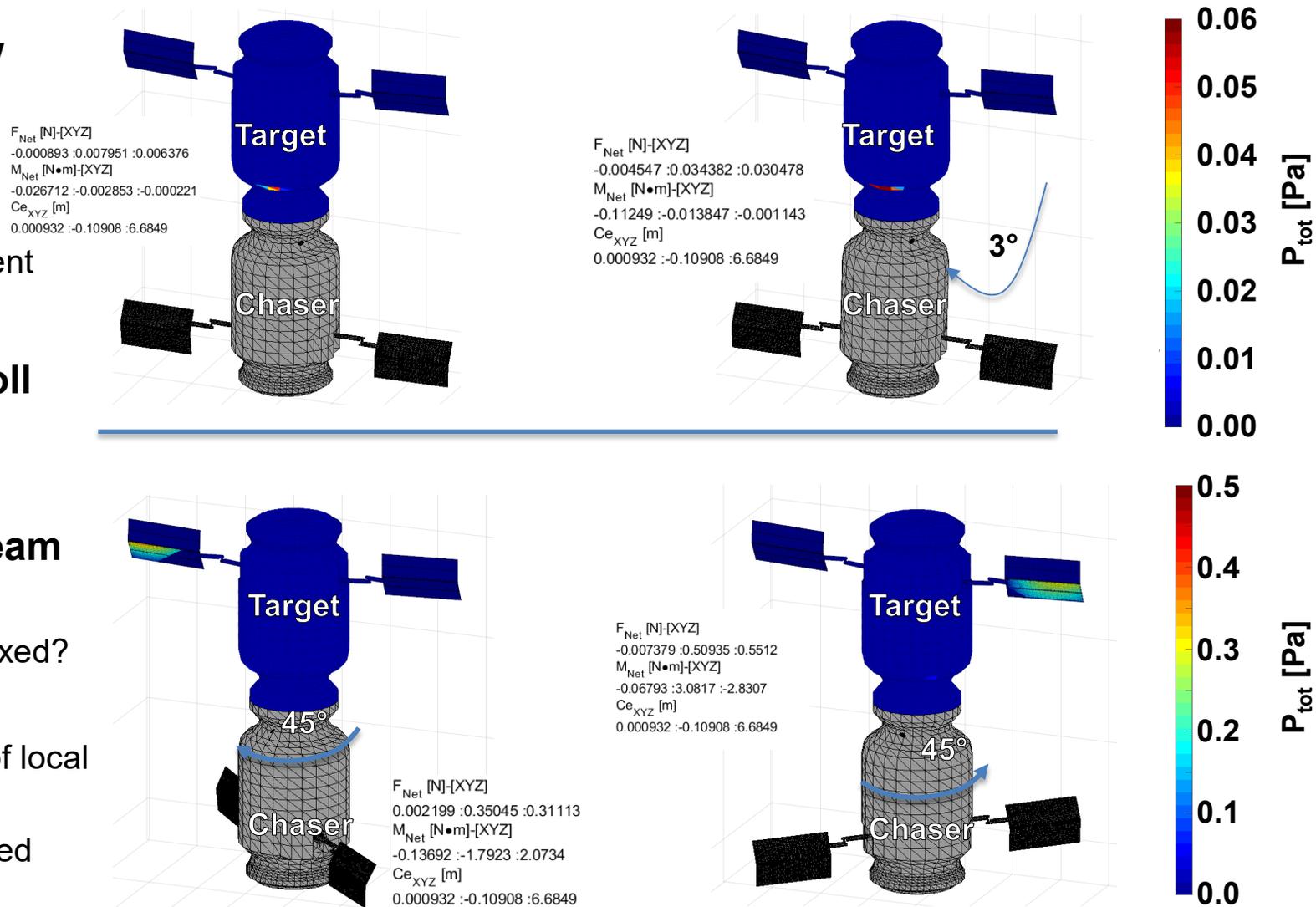
# Application of Simulation: LM Docking with Sphere

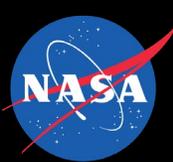


- **Change of 6 plume force/moments as function of “to docked” distance**
- **This model can be spline fit for a low fidelity GNC simulation with thruster firing history & closed loop functions**
  - Only 4 thrusters shown, forward Z<sup>+</sup>
  - Y forces exceed X forces due to thruster orientation
  - As expected, Z forces are largest
    - Potential concern arises for solar array position at high roll displacement
- **At 15m out, negligible impact**
  - Forces & Moments are all zero
- **Within 5 m of docking, M<sub>y</sub> exhibits an inversion in magnitude**
  - Indicates higher fidelity ΔZ would be warranted in mission planning phase



- In the event of docking abort how much plume is there?
  - e.g. fail to latch
  - Or separation of mated vehicles
  - Restrain to given angular displacement
- Repeat test for each thruster
- At  $\Delta Z=0$ , and various yaw/pitch/roll
  - Forces on the order of mN to 0.5 N
  - Moments order of 10 mN·m to N·m
- Based on analysis, give design team options:
  - Is the outer mold line of the vehicle fixed?
  - Can thruster angles be changed?
  - Magnitude indicates low probability of local heating concerns
  - For repeated docking events, expected surface contamination is low



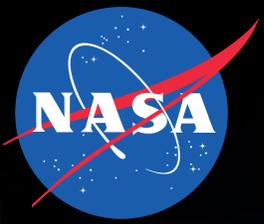


## Conclusions

- **An augmented viewfactor plume code was developed for rapid analysis of rendezvous and proximity operations of in space vehicles using MMH-NTO 400N thrusters**
- **An example mission was provided showing some use cases and design/analysis points**

## Future Work

- **Superimpose shear effects**
- **Expand the code to other prop systems**
- **Incorporate plume heating model**
- **Apply the code for the refinement of Gateway and other Logistics Services**



# Thank You



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# Questions?



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