Multiscale Modeling to Enable Physics-Based Simulations of Plume-Surface Interactions with Quantified Uncertainty

Topic 3 – *Rocket Plume-Surface Interaction Prediction Advancements*

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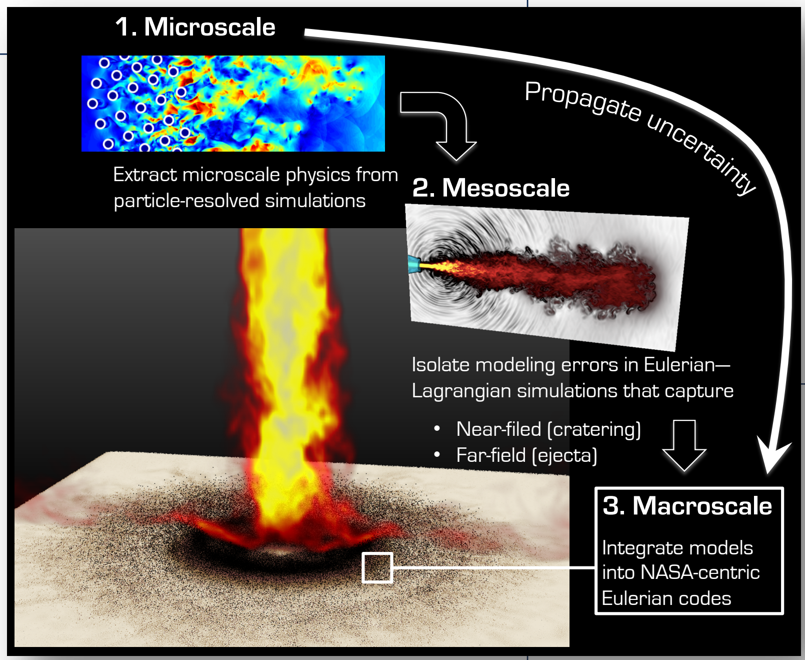
Approach

- **Develop closure for gas-particle microphysics** by spatially-filtering particle-resolved numerical simulations that capture all relevant hydrodynamics
- Integrate new models into Eulerian—Lagrangian simulation framework to **characterize particle-particle and gas-particle interactions** (erosion, cratering, ejecta) and inform new constitutive models used in Eulerian-based codes
- **Use hierarchical Bayesian inference** to estimate individual variations in modeling parameters at each scale over the span of relevant Mach numbers, ambient pressures, and engine thrusts
- Embed data-driven constitutive models with associated uncertainty into existing NASA codes



Research Objectives

Goal: Establish **advanced physics-based models** to enable predictive simulations of plume-surface interactions (PSI) with **embedded uncertainty** under relevant landing conditions

Key Innovations:

- **Address long-standing limitations in multiphase flow modeling** at finite Mach numbers and Reynolds numbers through a multiscale approach that connects flight-scale (*macroscale*) Eulerian models to two-phase statistics at the *microscale*
- **Uncertainty in modeling parameters will be propagated across scales** using non-intrusive and scalable Bayesian inference techniques

Comparison to SOA: Constitutive models that capture gas-particle and particle-particle interactions in compressible flows do not exit

Start TRL 2: Numerical framework in place

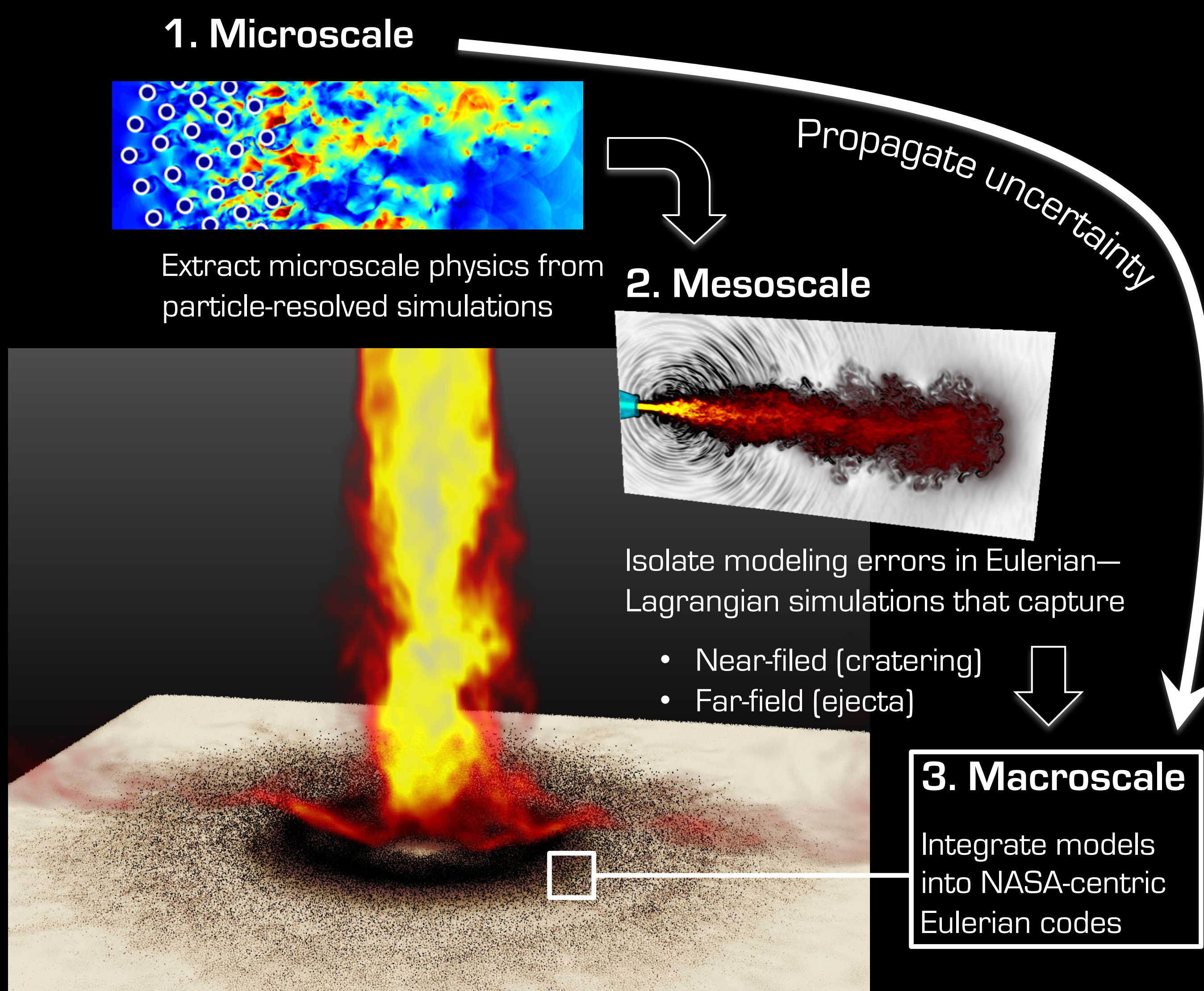
End TRL 3: Models validated against unit test cases and uncertainty quantified

Potential Impact

The success of future manned and robotic space exploration missions will require accurate modeling of rocket exhaust impingement during touchdown to design for risk and develop mitigation strategies

This ECF Award will enable large-scale predictive modeling capabilities to support NASA-centric Eulerian-based codes

- New Mach number-dependent drag coefficients, subgrid-scale turbulence closure, and particle-phase constitutive models
- Quantified uncertainty of the modeling parameters under extreme conditions relevant to landing events


1. Microscale
Extract microscale physics from particle-resolved simulations
Propagate uncertainty
2. Mesoscale
Isolate modeling errors in Eulerian–Lagrangian simulations that capture
• Near-filed (cratering)
• Far-field (ejecta)
3. Macroscale
Integrate models into NASA-centric Eulerian codes