**Introduction and Objective**

- Program used to simulate atmospheric flight trajectories of entry capsules [1]
- Includes models of atmospheres of different planetary destinations – Earth, Mars, Venus, Jupiter, Saturn, Uranus, Titan, ...
- Solves 3-degrees of freedom (3DoF) equations for a single body treated as a point mass
- Also supports 6-DoF trajectory simulation and Monte Carlo analyses
- Uses Fehlberg-Runge-Kutta (4th-5th order) time integration with automatic step size control
- Includes rotating spherical planet with gravitational field having a J2 harmonic
- Includes a variety of engineering aerodynamic and heat flux models
- Capable of specifying events – heatshield jettison, parachute deployment, etc. – at predefined altitudes or Mach numbers
- Has material thermal response models of typical aerospace materials integrated

**Modifications Made to Traj for Meteor Simulation**

- NASA’s Galileo probe to Jupiter only one that experienced significant mass loss
- Entry capsule was a 45° sphere-cone with fully-dense carbon phenolic as heatshield material
- M. Tauber et al. [2] developed JAE code for simulation of Galileo probe (Jupiter entry)
- JAE logic incorporated into Traj
  - Sphere-cone shape replaced by sphere
  - Mass loss equation of meteor physics used
  - Allow input specification of heat of ablation, Q
  - Allow heat transfer coefficient to vary in time
  - Time-varying heat transfer coefficients from detailed flow computations curve fit as a function of altitude, velocity, and size

**Traj Features:**

- **Test Case: Chelyabinsk [3]**
  - Basic Assumptions:
    - Hyperbolic excess velocity: 15.0 km/s
    - Altitude at entry: 95.0 km
    - Relative velocity at entry: 19.0 km/s
    - Relative entry angle: -18.5 deg
    - Relative heading angle: -76.6 deg
    - Geographic latitude at entry: 54.5 deg
    - Oblate rotating Earth
    - Gravitational model includes J2 term
    - US-1976 atmospheric model
  - Meteoroid Assumptions:
    - Shape: Sphere
    - Density of meteoric material: 3300 kg/m³
    - Aerodynamic model: Sphere
  - Sensitivity study to entry mass, heat transfer coefficient, heat of ablation, and fragmentation

**Test Case: Chelyabinsk [3]**

- Heat Transfer Coefficient, $C_H$, Model
  - $C_H(z) = \left[ a + b(\frac{z}{J})^c \right] \exp\left( \frac{z - C}{J} \right)$
  - Curve fit expressions are to be used for $z > 15.5 \text{ km}$
  - $C_H$ for different velocities and diameters obtained through linear interpolation

- **Basic Plots for Variable $C_H$ and Double Fragmentation (Case 2_D)**
  - For Case 2_D simulation fragmentation at 40 & 30 km altitudes assumed to occur instantly
  - Fragment masses tuned to overlay simulated trajectory on Chelyabinsk observations.
  - On a scale of 40 to 90 km altitude, mass vs altitude trace appears to be a straight line over the entire mass range
  - Trace is actually parabolic when mass scale is expanded
  - Influence of $C_H$ model is insignificant if large changes occur in meteor mass due to fragmentation

**Conclusions, Future Work and References**

- **TRAJ**, an established trajectory simulation tool successfully modified for meteor entries
- Improvements include:
  - Simple mass loss equation of meteor physics
  - Time-varying heat transfer coefficient based on detailed flow computations
  - Ability to specify fragmentation events
  - Updated version of Traj tested against Chelyabinsk observations
- **TRAJ** can now be used to establish sensitivity of trajectories to various meteor parameters
- Leaves open the issue of verification/validation of Traj and additional test cases are needed
- Could tektites [4] be used as additional test cases?
- Advantages of simulating tektite entries into Earth’s atmosphere
  - Exo-atmospheric shapes are definitely spherical
  - Small sizes and (sub)orbital entry velocities
  - Problem is dominated by convective heating and melting
  - Melted shapes are aerodynamically stable
  - Chemical composition of australite tektites is statistically well defined
  - Serve as a good foundation for the tougher meteor entry problem

**References**