Implementation of a Landing Footprint Algorithm for the HTV-2 and Trajectory Simulations

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Controls and Dynamics

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Overview

- Landing Footprint Generation
  - Motivation
  - Problem Set-Up
  - Explanation of the Algorithm
  - Results
- OTIS Trajectory Simulations
  - MIPCC F-15 Performance Estimation
  - HTV-2
- Two week tour in the Engine Shop

Task 1:

Landing Footprint Generation

Motivation

- A landing footprint provides an estimate of the flyable boundary for a vehicle given initial conditions
- Current research for re-entry guidance is moving towards onboard trajectory generation
- Generation of a landing footprint will clearly define possible landing sites in the event of a vehicle malfunction
- It is critical for the algorithm to be executable in near real-time and provide a realistic estimate of the footprint, taking into account vehicle limitations

Problem Set-Up

- Entry Dynamics
  - $\theta' = -\frac{\cos(\gamma)\cos(\psi)}{rcos(\phi)}\left(\frac{1}{D}\right)$
  - $\phi' = -\frac{\cos(\gamma)\sin(\psi)}{r}\left(\frac{1}{D}\right)$
  - $r' = -\sin(\gamma)\left(\frac{1}{D}\right)$
  - $\psi' = \frac{\cos(\psi)\tan(\phi)\cos(\gamma)}{r} + \left(\frac{1}{V^2\cos(\gamma)}\right)\left(\frac{Lsin(\sigma)}{D}\right) + C_\psi$
  - $\gamma' = \left(g - \frac{V^2}{r}\right)\left(\frac{\cos(\gamma)}{V^2}\right)\left(\frac{1}{D}\right) - \left(\frac{1}{V^2}\right)\left(\frac{L}{D}\cos(\sigma)\right) + C_\gamma$
- Derivatives taken with respect to energy, $E = \frac{V^2}{2} - \frac{mu}{r}$
- Control variables are angle of attack and bank angle

Saraf, A., Leavitt, J. A., Mease, K. D., and Ferch, M., "Landing Footprint Computation for Entry Vehicles," AIAA 2004-4774, 2004.

Problem Set-Up

- Lift and Drag

$$L = \frac{1}{2}\rho(r)V^2\left(\frac{S}{m}\right)\mathrm{C_L}(\alpha, M)$$

$$D = \frac{1}{2}\rho(r)V^2\left(\frac{S}{m}\right)C_D(\alpha, M)$$

- Taking the derivative of Drag twice yields:

$$\frac{L}{D}cos\sigma = \frac{1}{b}(D'' - a)$$

$$a = D\left(\frac{C_D''}{C_D} - \frac{C_D'^2}{C_D^2}\right) + D'\left(\frac{C_D'}{C_D} + \frac{2}{V^2}\right) - \frac{4D}{V^4} + \frac{1}{DV^2}\left(\frac{1}{h_s} + \frac{2g}{V^2}\right)\left(g - \frac{V^2}{r}\right) + \left(\frac{1}{h_s} + \frac{2g}{V^2}\right)C_\gamma$$

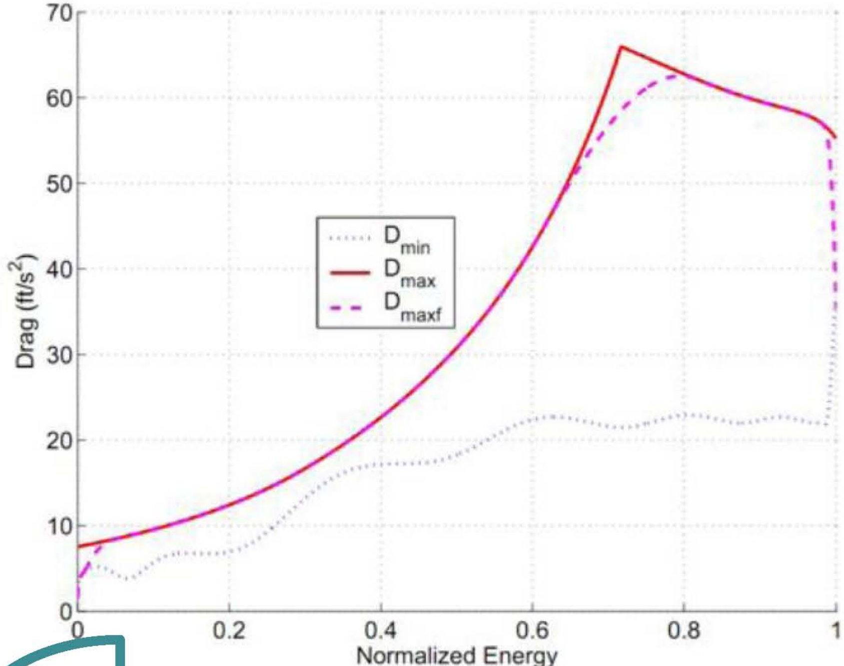
$$b = -\frac{1}{V^2}\left(\frac{1}{h_s} + \frac{2g}{V^2}\right)$$

- Re-arrange and solve for bank angle

$$|\sigma| = \cos^{-1}\left(\frac{D}{bL}(D'' - a)\right)$$

The Algorithm

- Method the algorithm employs requires the computation of upper, lower, and intermediate drag profiles
  - These drag profiles are used to create the boundary points of the footprint
  - To do this, a nominal angle of attack profile is required



Sample Drag Boundaries

$$\tilde{E} = \frac{E_{current} - E_i}{E_f - E_i}$$

The Algorithm

- Computing the Flyable Upper Drag Boundary:
  - Path Constraints:
    - Dynamic Pressure:

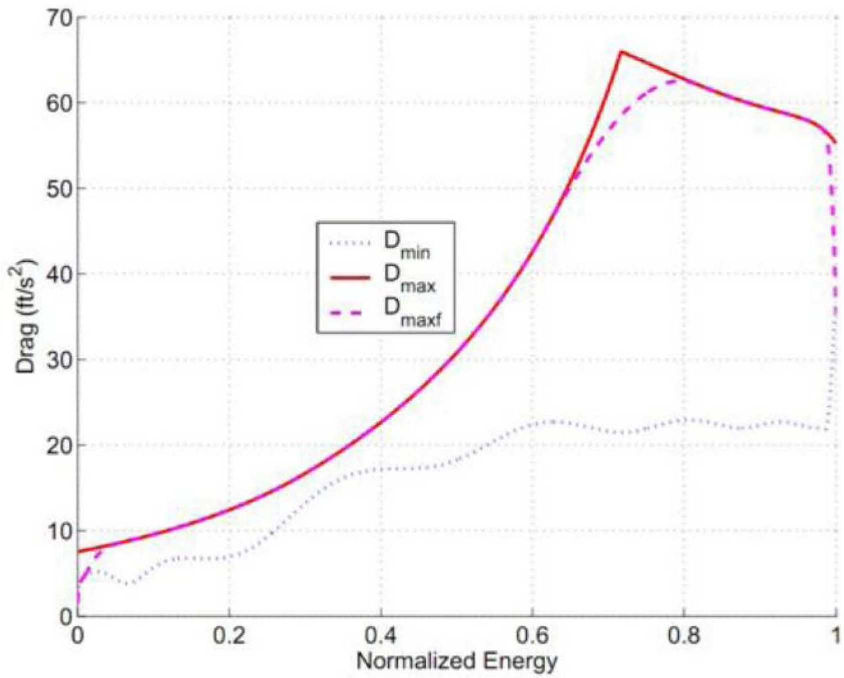
$$D < Q_{max}\left(\frac{S}{m}\right)C_D$$

    - Normal Acceleration:

$$D < \frac{A_{max}}{sin\alpha + \frac{L}{D}\cos\alpha}$$

    - Heating:

$$D < \frac{1}{2}\left(\frac{\dot{Q}_{max}}{cV^k}\right)^2 V^2 S C_D$$



The Algorithm

- Flyable lower drag boundary
  - Determined by the equilibrium glide condition: $\gamma' = 0$ and $\sigma = 0$

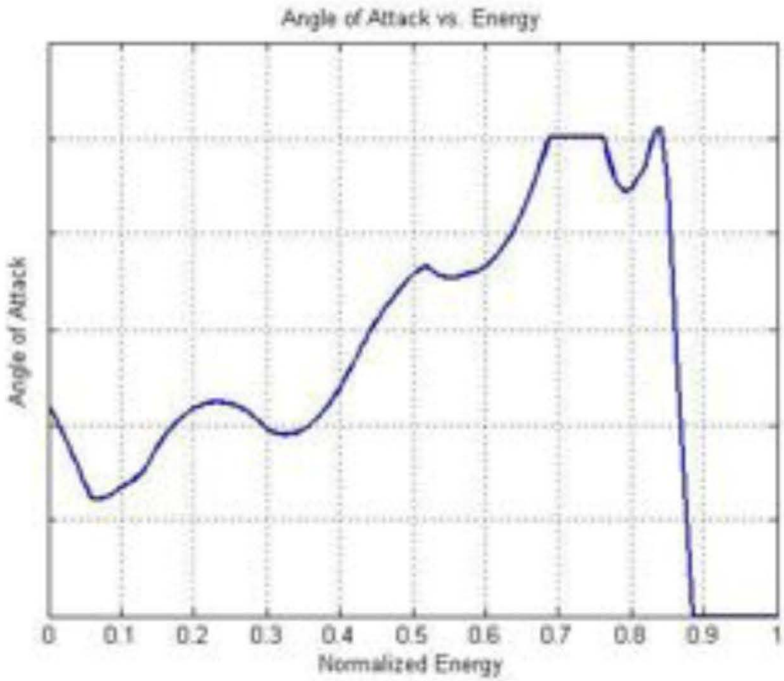
$$\gamma' = \left(g - \frac{V^2}{r}\right)\left(\frac{\cos(\gamma)}{V^2}\right)\left(\frac{1}{D}\right) - \left(\frac{1}{V^2}\right)\left(\frac{L}{D}\cos(\sigma)\right) + C_\gamma$$

$$0 = \left(g - \frac{V^2}{r}\right)\left(\frac{1}{V^2}\right)\left(\frac{1}{D}\right) - \left(\frac{1}{V^2}\right)\left(\frac{L}{D}\right)$$

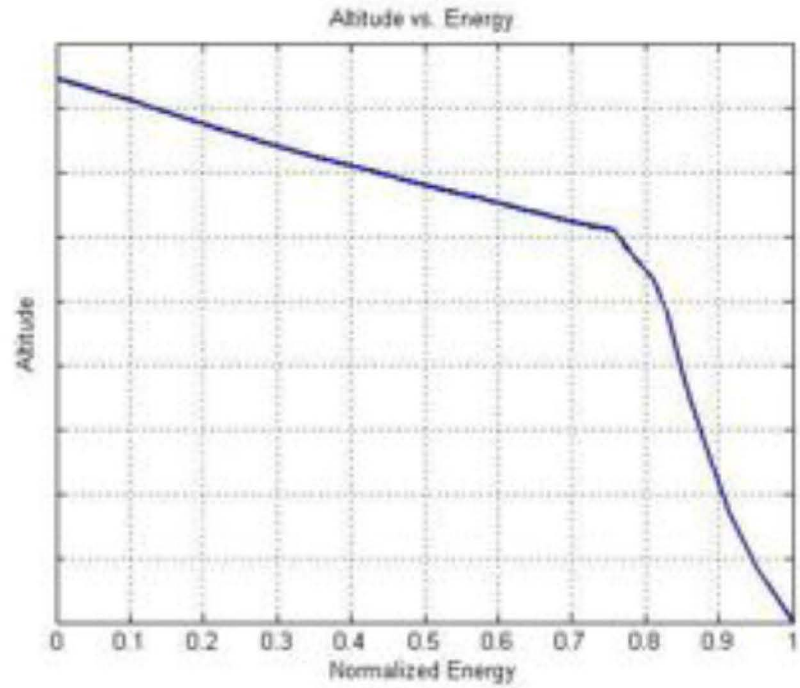
$$L = \left(g - \frac{V^2}{r}\right) \rightarrow D_{min} = \frac{C_D}{C_L}\left(g - \frac{V^2}{r}\right)$$

- Intermediate drag values are interpolated from the maximum and minimum drag profiles
  - $D(E) = D_{max}(E) + c(D_{min}(E) - D_{max}(E))$

Simulated HTV-2 Data

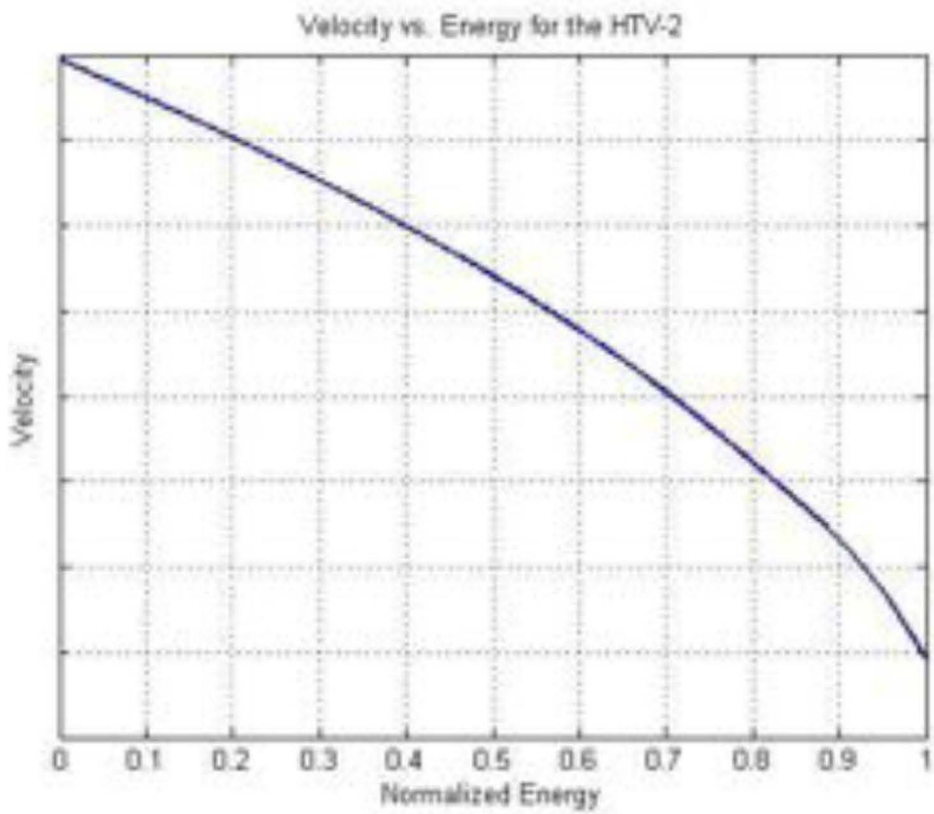


Angle of Attack Profile



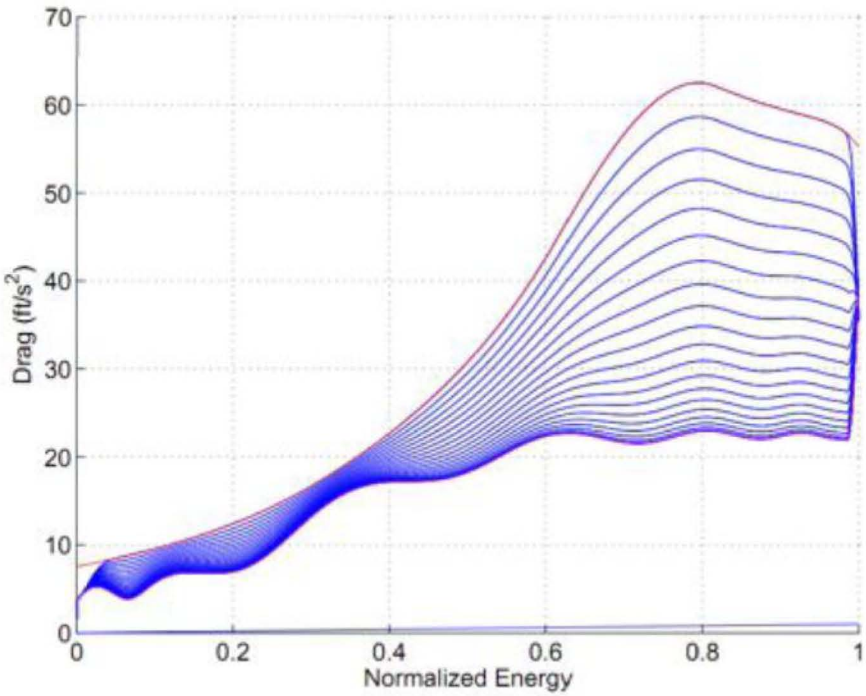
Altitude Profile

Simulated HTV-2 Data

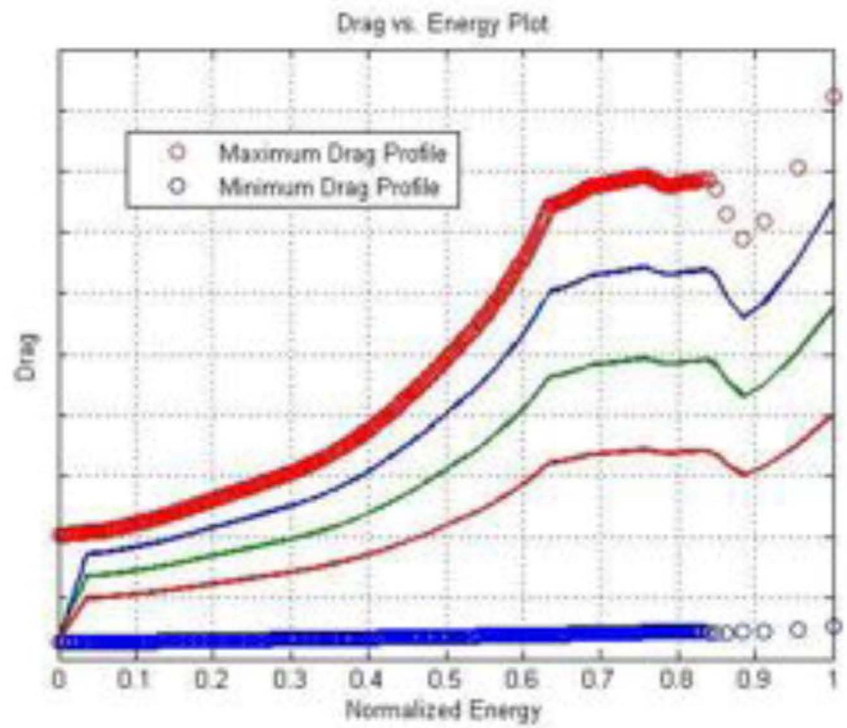


Velocity Profile

Drag Profile Results

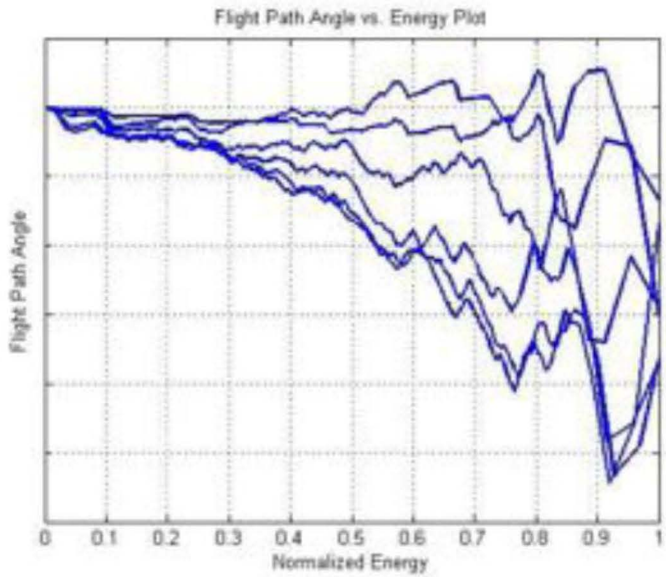


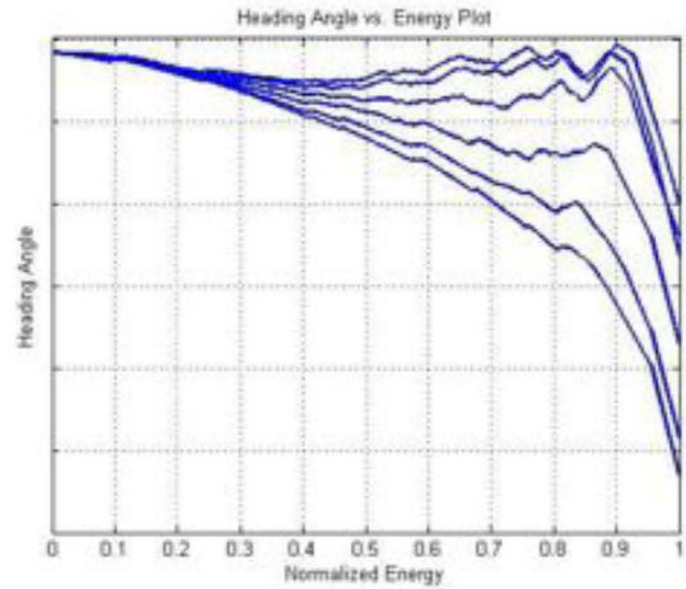
Sample Drag Profile from the Paper

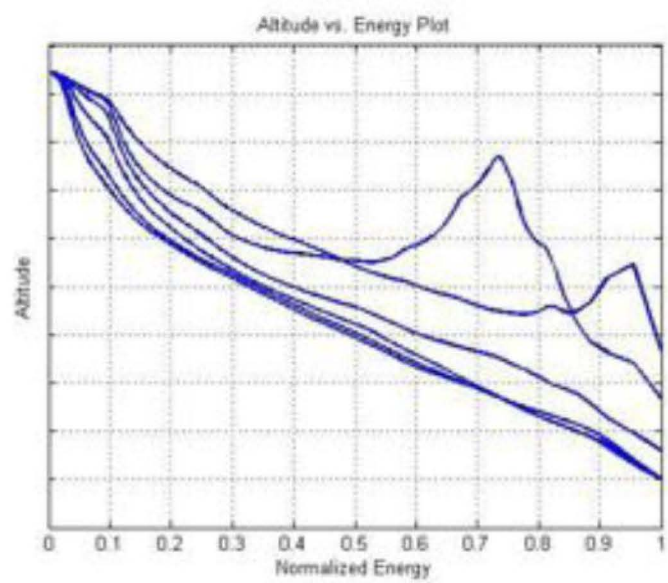


Drag Profile Result

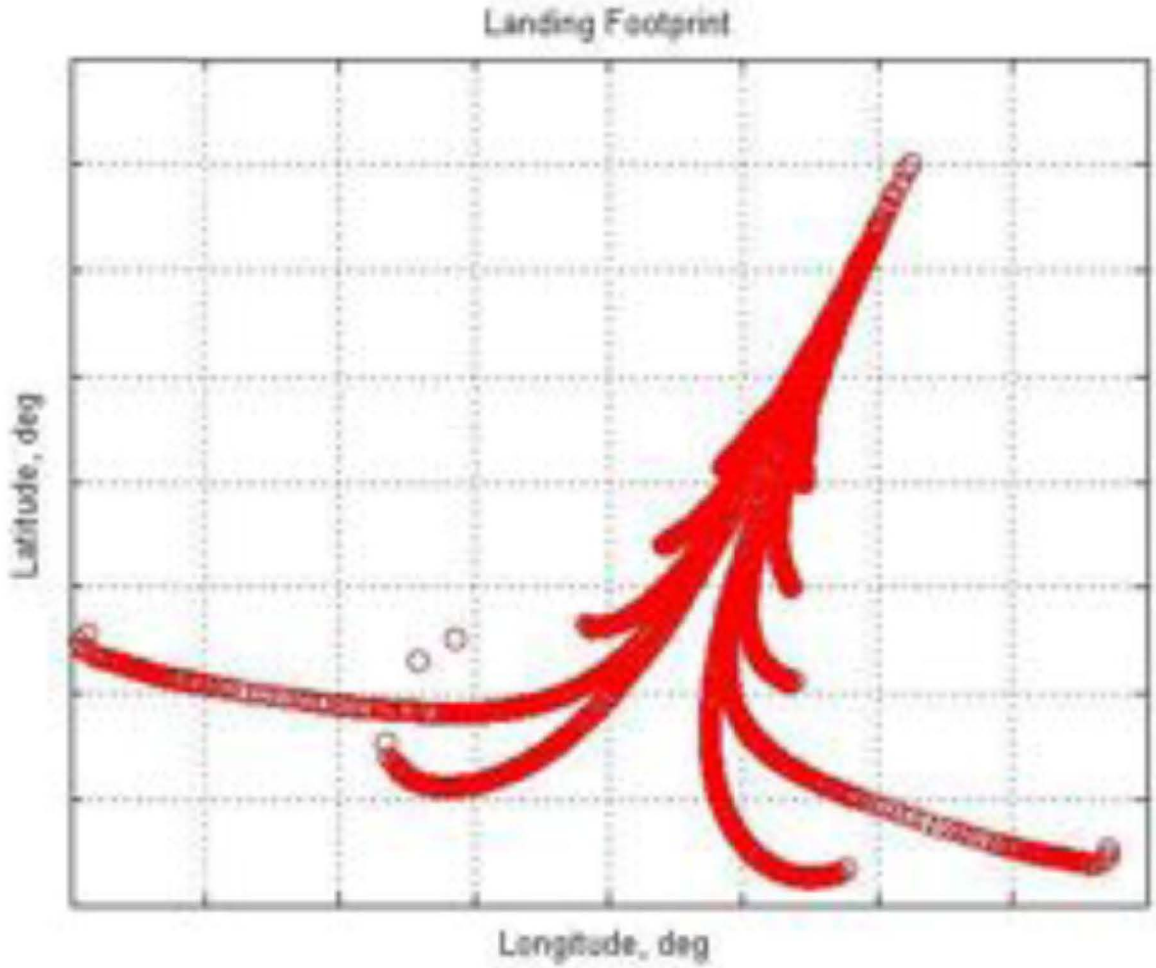
Further Results







Resulting Footprint



Future Work

- The lower drag boundary can be improved upon by adding the constraint that $\gamma \leq 0.01$ to reduce phugoid motion
  - A feedback linearization based flight path controller is used:

$$\frac{L}{D} cos\sigma = \frac{K_\gamma V}{D}(\gamma_{ref} - \gamma) + \frac{1}{D}\left(g - \frac{V^2}{r}\right) cos\gamma - \frac{2\omega V}{D} cos\psi cos\phi$$

- Obtain the correct constraint parameters to obtain an accurate drag curve, and thus a more accurate footprint
- Improve the speed of the algorithm
  - Paper claims 2 seconds, written in C
  - My result: 39.5 seconds for the footprint presented, 8.48 seconds to compute the drag profiles presented

Task 2:

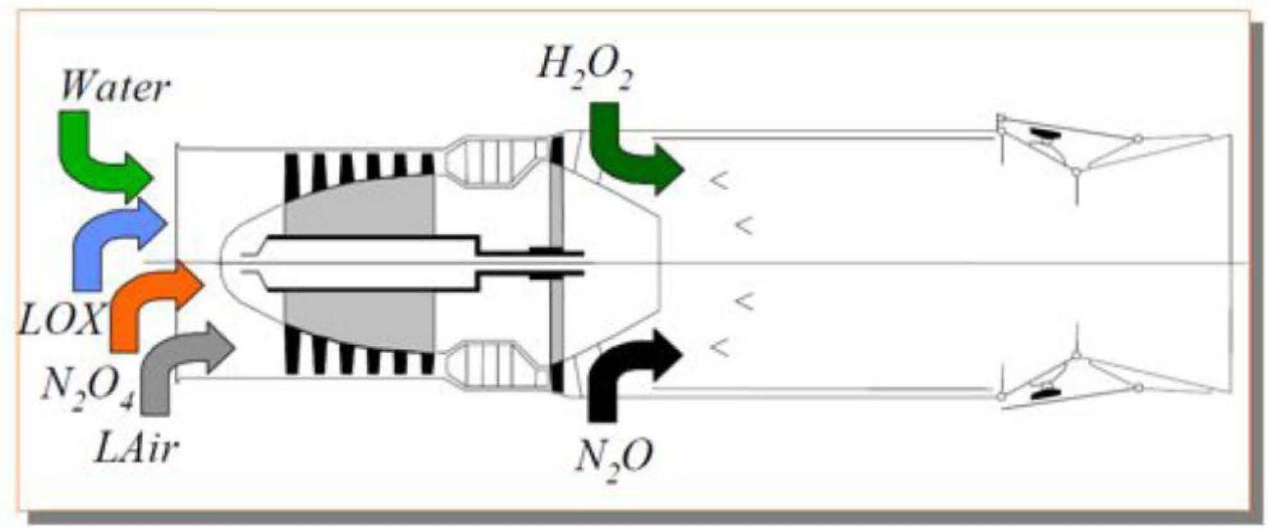
OTIS Trajectory Simulations

OTIS Overview

- OTIS: Optimal Trajectories by Implicit Simulation
- Largely 3DOF Simulation software that treats the inputted vehicle as a point-mass
- Aerodynamics, propulsion, and reference area data are inputted to define the vehicle
- Capable of explicit and implicit integration, as well as multi-phase trajectory problems
- Implicit integration techniques are used to optimize a user-specified parameter along a chosen trajectory

F-15 MIPCC Modeling

- MIPPC: Mass Injected Pre-Compressor Cooling
  - A mixture of LOX and water are injected into the engine at high altitudes and Mach numbers,
  - Theoretically provides increased performance by cooling the compressor face and providing increased mass flow

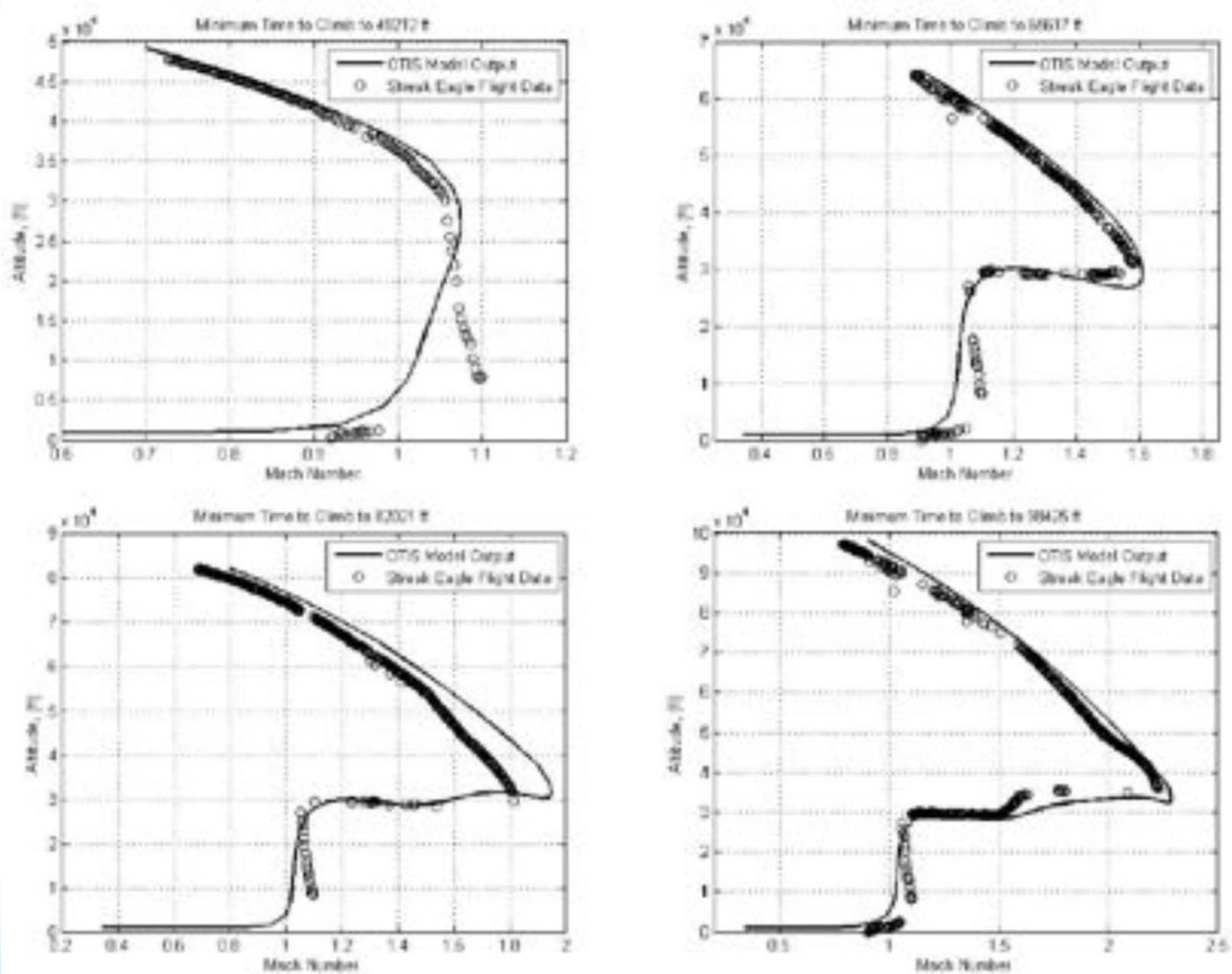


MIPCC Injection

Standard F-15 OTIS Sim

- Engine data for the Pratt & Whitney F100-100 was obtained from the Status Engine Estimated Steady State Performance Deck
  - Data extracted was for maximum throttle over a wide range of altitudes
- Aerodynamic data was obtained from flight test data presented in graphs provided in the paper by Haering and Burcham for a range of Mach and altitudes
  - Data was extracted from graphs using the MATLAB program Ascribe by David Berger
- Data was formatted and placed in an external file called by the main OTIS input file

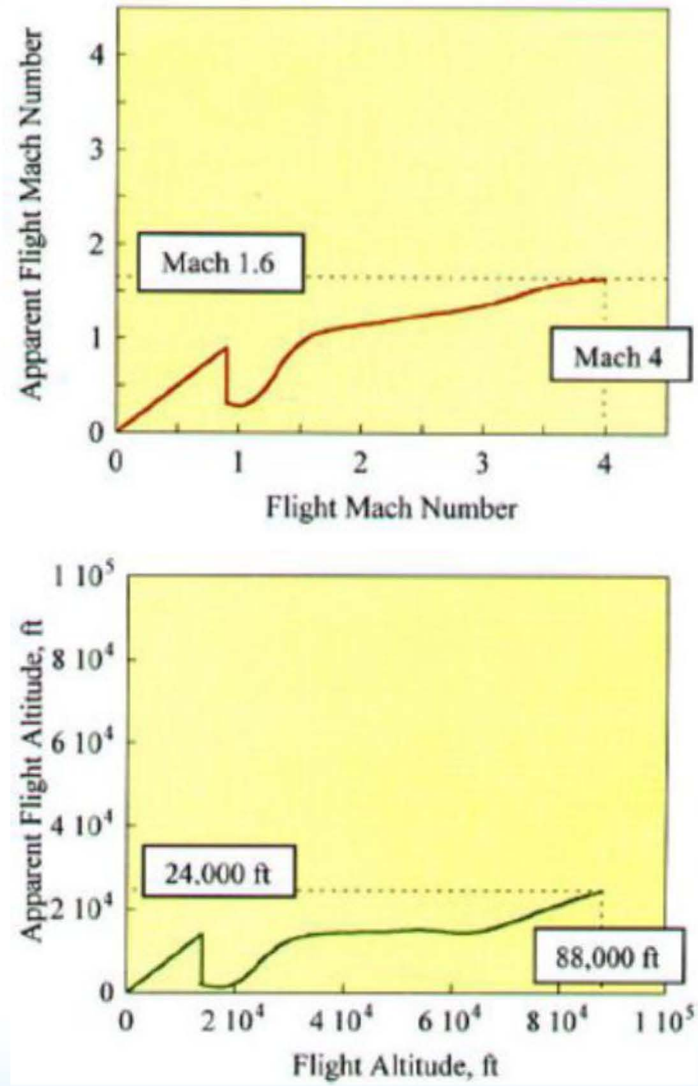
OTIS Calibration to F15 Streak Eagle



Min Time to Climb Results

MIPCC Modified F-15 OTIS Simulation

- Thrust and ISP data was inputted in accordance with predicted apparent Mach and Altitude
- MIPCC model was then run up to Mach 4 at a variety of altitudes
  - Explicit path used to verify Implicit integration
  - Energy was the chosen parameter to be optimized
    - $e = \frac{V^2}{2g_0} + alt$
- From OTIS, specific power curves and sample trajectories were outputted



Projected MIPCC Results (Carter, P.H.)

MIPCC Modified F-15 Sim: Results

- The study has been completed and the results are projected to appear in a NASA Technical Memorandum publication:
  - Kloesel, K.J., Clark, C.M., Hathaway, R., Berger, D., "MIPCC Enhanced F-4 and F-15 Performance Characteristics," NASA Technical Memorandum, (projected) 2011.

HTV-2 OTIS Simulation

- Work in progress…
- Explicit OTIS simulation complete
  - Trajectory begins at specified velocity, altitude, and weight and completes in the inputted time
- Implicit OTIS simulation still left to finish
  - Boundary conditions need to be added so that final energy state matches known data

Task 3:

Tour in the Engine Shop

The Engine Shop

- Provided hands-on experience
- During my two weeks…
  - Removed a mixer, A/B liner, pilot valves, distributer valves, spray bars, nozzle flaps, and a damaged flame holder, from an F404 engine
  - Aided in boroscoping 850, 852, and SOFIA
  - Watched an engine test run

Questions?

Works Cited

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- Haering, E.A. and Burcham, F.W., "Minimum Time and Fuel Flight Profiles for an F-15 Airplane with a Highly Integrated Digital Electronic Control System," *Nasa Technical Memorandum,* Vol. 86042, 1984.
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