RASAero II Flight Simulation Comparison with Kip Daugirdas MESOS 293K ft Altitude Rocket Flight Data

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Rogers Aeroscience

MESOS 293K ft Flight Kate Summary Data

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Â:              Flight Card
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Launch date:   Sat Oct 01 2022
Launch site:   Black Rock Desert Nevada
Flyer's name:  Kip Daugirdas
Rocket name:   MESOS
Motor:         O4500 M830
Expected alt:  250000 feet
Dual deploy:   Yes, main parachute set at 6000 feet

Comments: First flight of MESOS on October 1, 2022


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Â:                  Flight Results
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Max GPS altitude:    293488 feet AGL
Max Acc altitude:    294271 feet AGL
Max Baro altitude:   275131 feet AGL
Altitude at max vel: 62301 feet AGL

                    NOTE: Flight exceeded GPS velocity limit!
Max GPS velocity:   1673 feet/sec   1140.7 mph   1.656 Mach
Max Acc velocity:   4047 feet/sec   2759.3 mph   4.179 Mach

Max Acceleration:  15.6 G's   501.6 feet/sec/sec

                      Booster        Sustainer
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       Delay time:    0.0 sec        16.9 sec
       Burn  time:    6.2 sec        10.3 sec
 Max acceleration:   15.6 G's        11.5 G's
Tilt at  ignition:      0Â°           4.01Â°
Ignition altitude:      0 feet      35707 feet
Burn out altitude:   8623 feet      62316 feet
Ignition velocity:      0 ft/s       1030 ft/s
Burn out velocity:   2428 ft/s       4047 ft/s
Ignition velocity:   0.00 Mach       1.06 Mach
Burn out velocity:   2.24 Mach       4.18 Mach
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Apogee Deployment Event
Occurred:  150.0 sec after liftoff
Fired:     4.26 sec early
Altitude:  293266 feet
Vert vel:  119 feet/sec

Distance to apogee:  55767 feet
Bearing  to apogee:  318Â° from true north

Descent rate on drogue: 1673 feet/sec   1140.7 mph
Touch down velocity:      21 feet/sec     14.3 mph

Main Parachute Deployment Event
Deployed:  710.6 sec after liftoff
Altitude:  5968 feet AGL
Vert vel: -112 feet/sec

Time to max velocity:       33.3 sec
Time to apogee:       2 min 34.3 sec
Time on drogue:       9 min 16.3 sec
Time on main:         3 min  2.6 sec
Total flight time:   14 min 53.2 sec

Lift off:     11:30:58.0 MDT    17:30:58.0 UTC
Apogee:       11:33:32.2 MDT    17:33:32.2 UTC
Touch down:   11:45:51.2 MDT    17:45:51.2 UTC

Launch  pad  coordinates:  N 40Â° 52.2209'  W 119Â°  6.4851'

Ground level: 3910 feet MSL

              Liftoff    Apogee     Landing
Battery:      4.04v      3.97v      3.87v
Temperature:   83Â°F      100Â°F      107Â°F

Transmitter:  Mx210A0519  Firmware: 7.4.0.8

This data came from transmitter flash memory.
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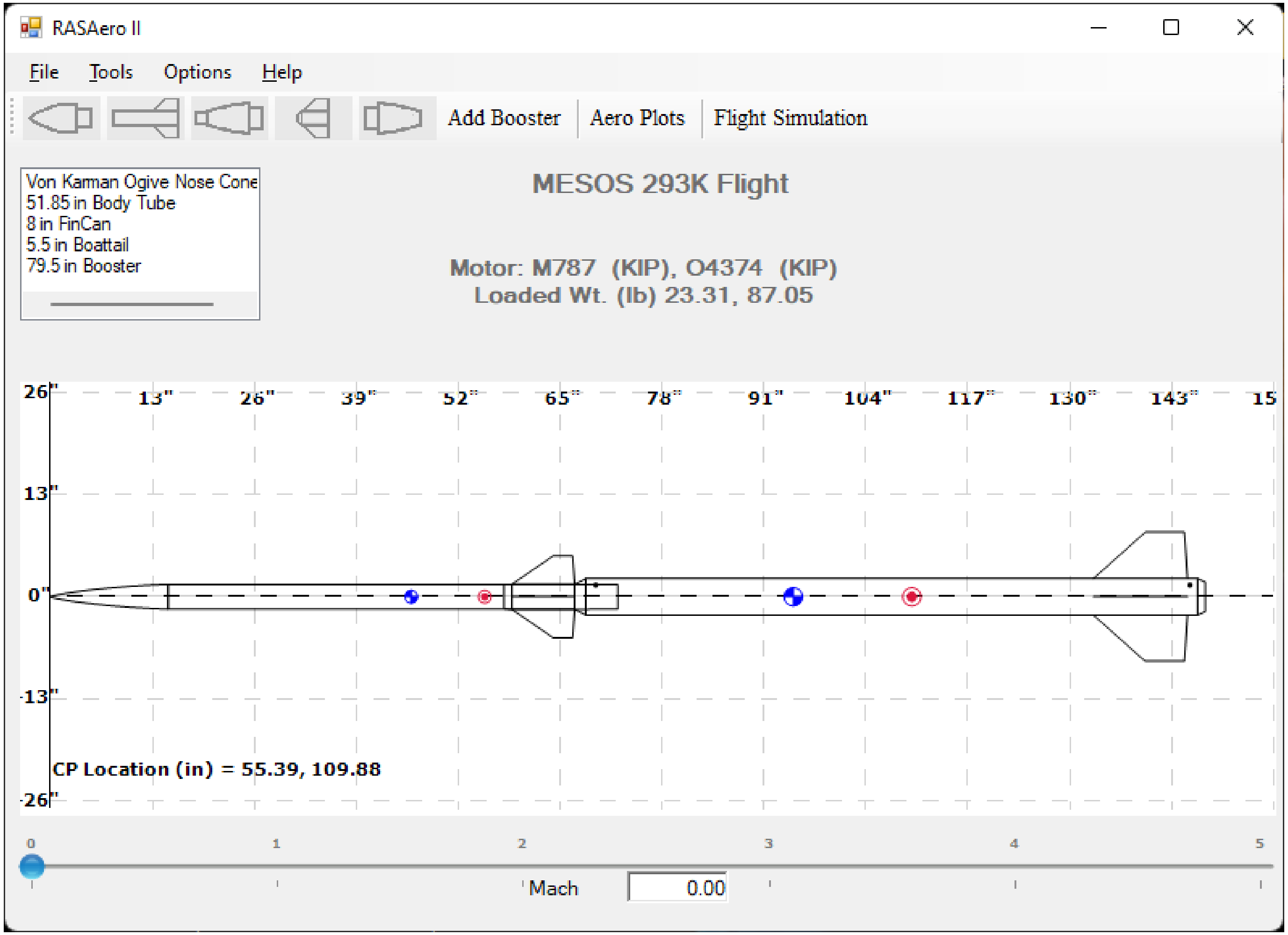
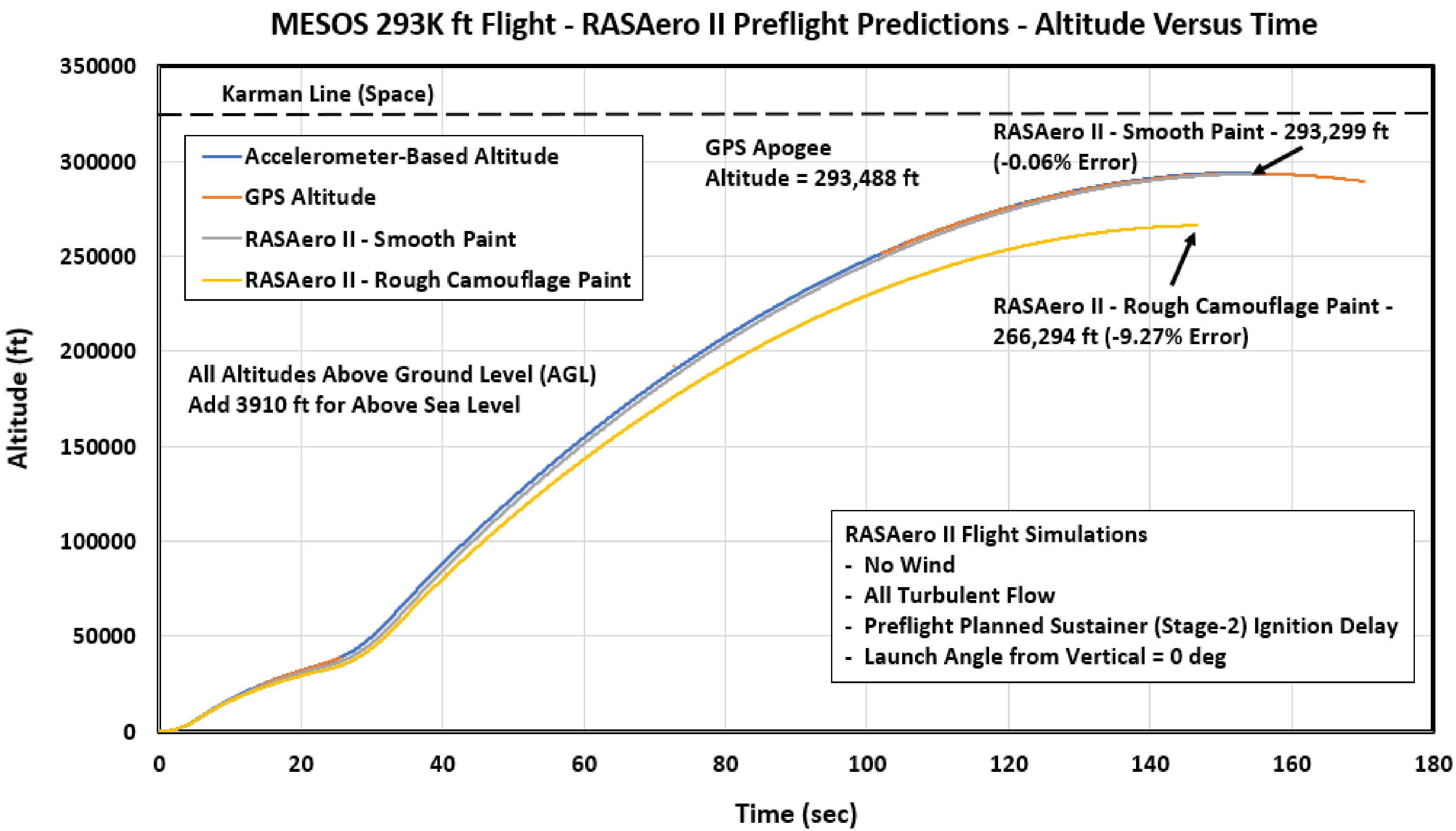
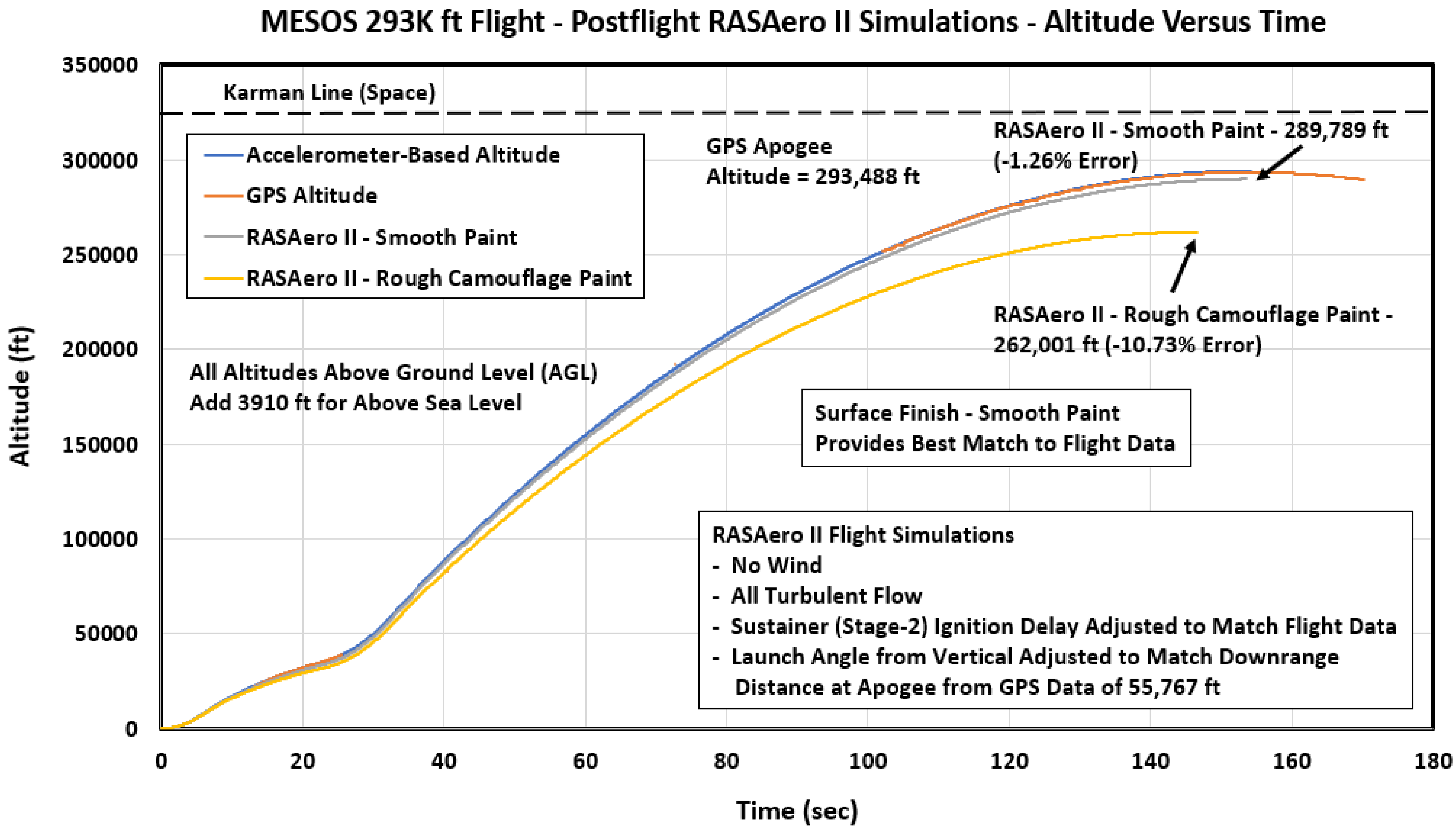
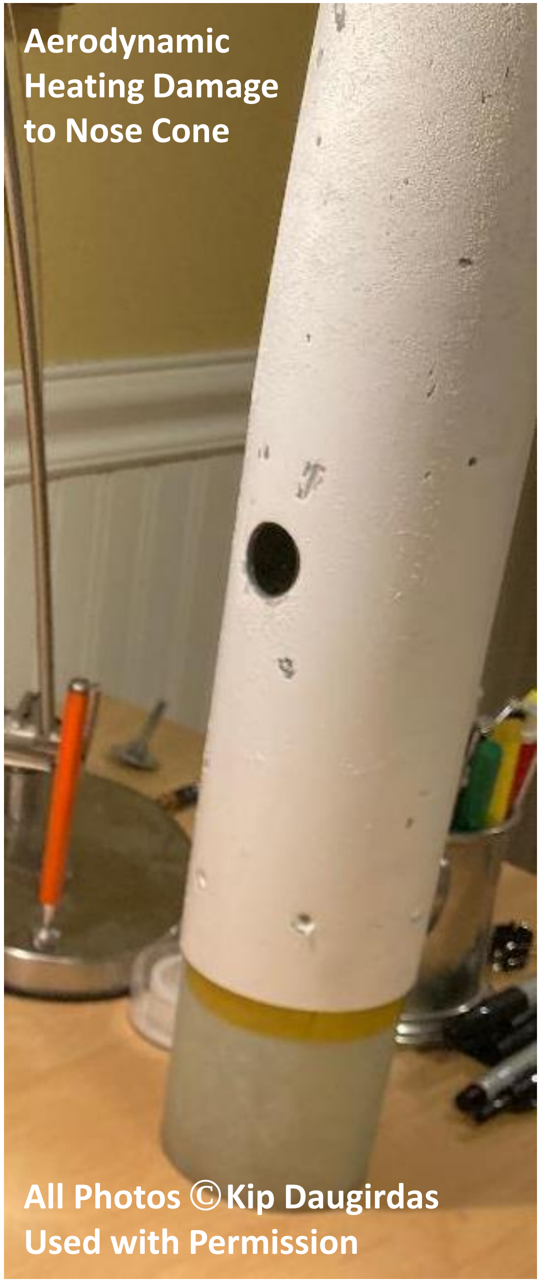
MESOS 293K ft Flight RASAero II Rocket Input Geometry (Scale Rocket Drawing)



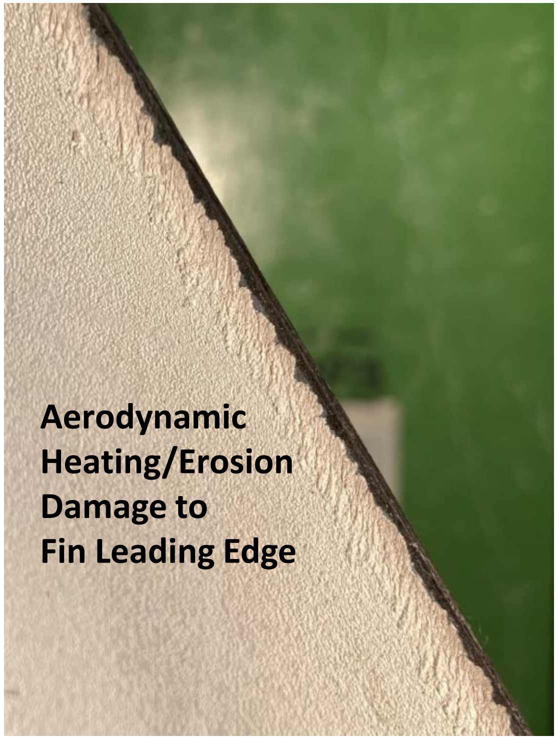

MESOS 293K ft Flight - RASAero II Preflight Predictions - Altitude Versus Time
Karman Line (Space)
Accelerometer-Based Altitude
GPS Altitude
RASAero II - Smooth Paint
RASAero II - Rough Camouflage Paint
GPS Apogee
Altitude = 293,488 ft
RASAero II - Smooth Paint - 293,299 ft
(-0.06% Error)
RASAero II - Rough Camouflage Paint -
266,294 ft (-9.27% Error)
All Altitudes Above Ground Level (AGL)
Add 3910 ft for Above Sea Level
RASAero II Flight Simulations
- No Wind
- All Turbulent Flow
- Preflight Planned Sustainer (Stage-2) Ignition Delay
- Launch Angle from Vertical = 0 deg
Altitude (ft)
Time (sec)
0
50000
100000
150000
200000
250000
300000
350000
0
20
40
60
80
100
120
140
160
180

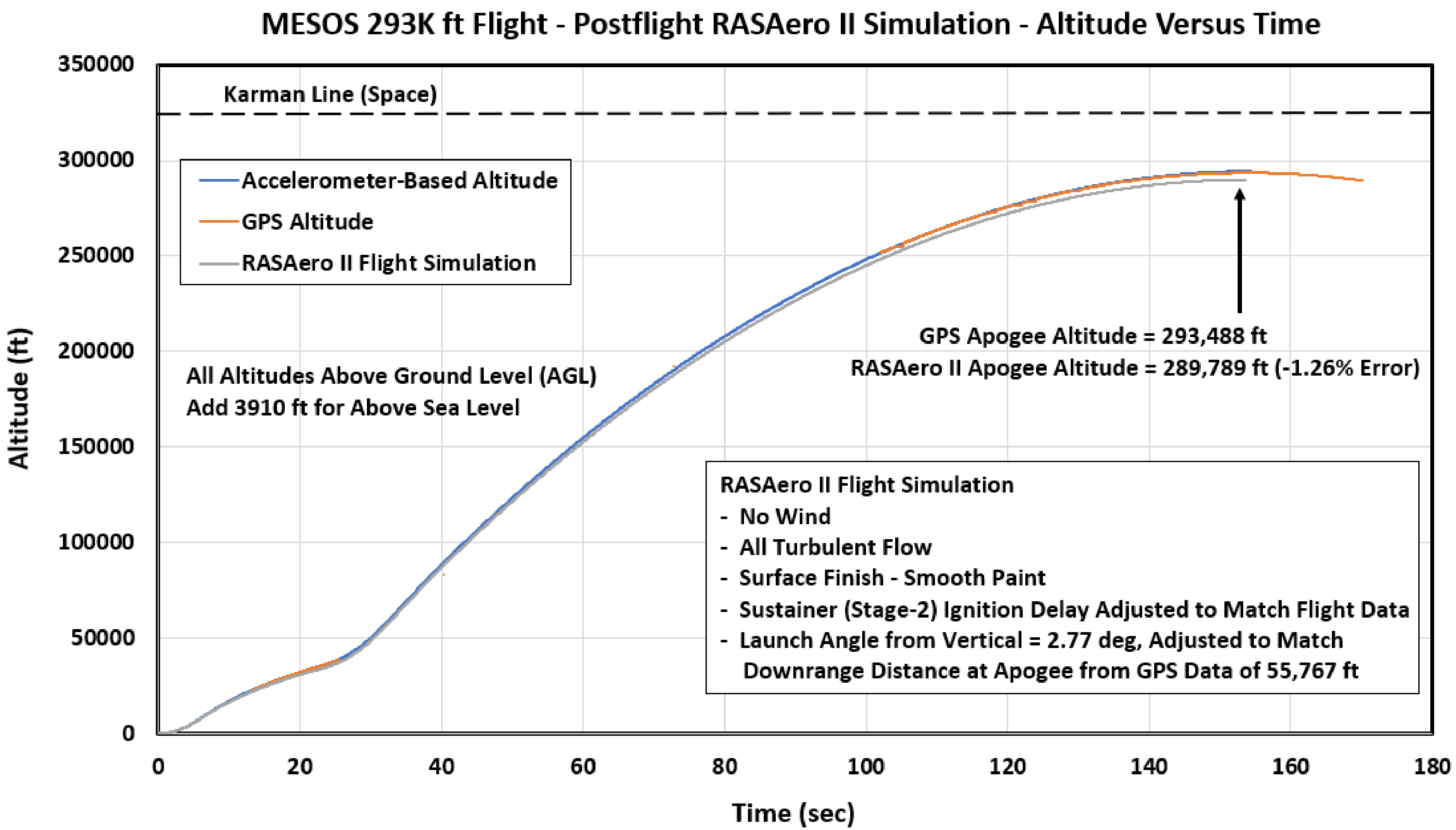


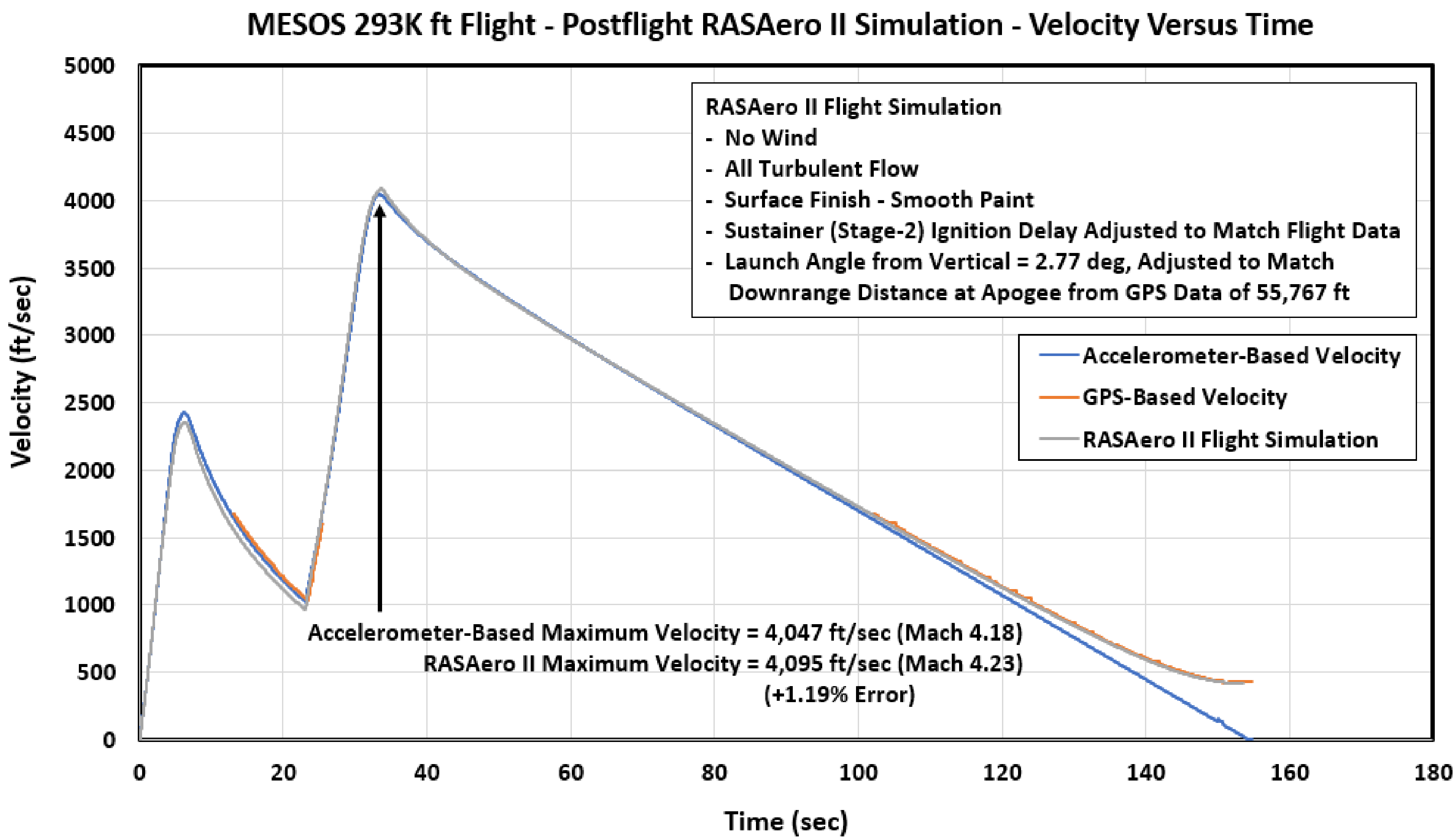
MESOS 293K ft Flight - Postflight RASAero II Simulations - Altitude Versus Time
Karman Line (Space)
Accelerometer-Based Altitude
GPS Altitude
RASAero II - Smooth Paint
RASAero II - Rough Camouflage Paint
GPS Apogee
Altitude = 293,488 ft
RASAero II - Smooth Paint - 289,789 ft
(-1.26% Error)
RASAero II - Rough Camouflage Paint -
262,001 ft (-10.73% Error)
All Altitudes Above Ground Level (AGL)
Add 3910 ft for Above Sea Level
Surface Finish - Smooth Paint
Provides Best Match to Flight Data
RASAero II Flight Simulations
- No Wind
- All Turbulent Flow
- Sustainer (Stage-2) Ignition Delay Adjusted to Match Flight Data
- Launch Angle from Vertical Adjusted to Match Downrange
Distance at Apogee from GPS Data of 55,767 ft
Altitude (ft)
Time (sec)
0
50000
100000
150000
200000
250000
300000
350000
0
20
40
60
80
100
120
140
160
180

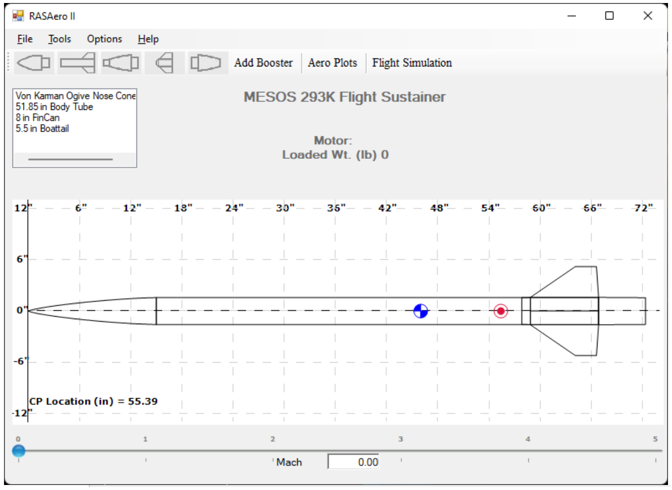


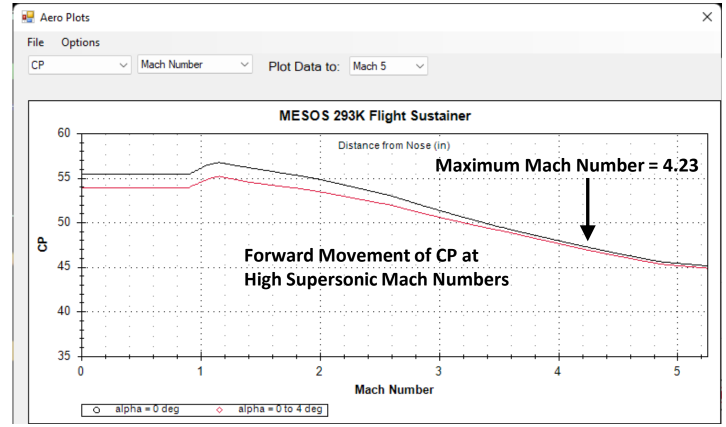
- Surface Damage to Rocket from Mach 4 Aerodynamic Heating and Erosion from High Dynamic Pressure
  - From Roughing Up of Surfaces had Recommended Using Surface Finish of Rough Camouflage Paint for Mach 3 Flights, and Flights Over Mach 3
- Effect of Increased Surface Roughness Apparently Not as Significant as Expected
- Surface Finish of Smooth Paint Provided Better Match to Flight Data than Rough Camouflage Paint
- Final Postflight RASAero II Flight Simulation Run with Surface Finish Set To Smooth Paint

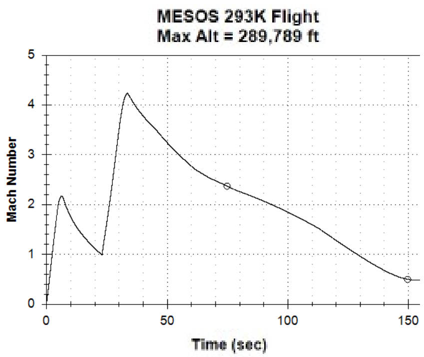


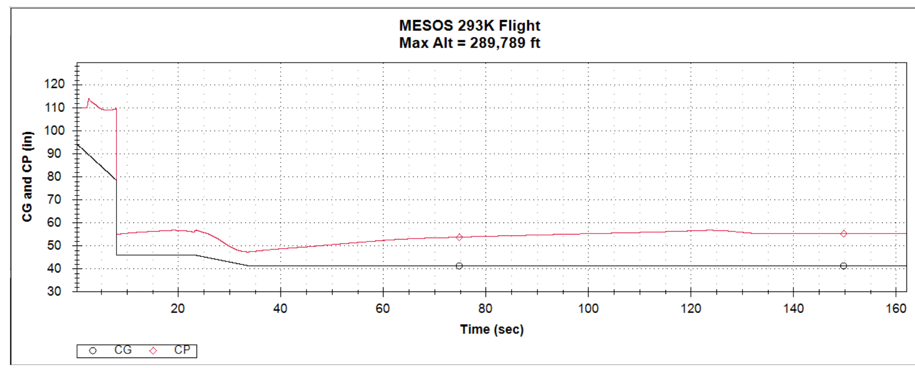

MESOS 293K ft Flight - Postflight RASAero II Simulation - Altitude Versus Time
Karman Line (Space)
Accelerometer-Based Altitude
GPS Altitude
RASAero II Flight Simulation
GPS Apogee Altitude = 293,488 ft
RASAero II Apogee Altitude = 289,789 ft (-1.26% Error)
All Altitudes Above Ground Level (AGL)
Add 3910 ft for Above Sea Level
RASAero II Flight Simulation
- No Wind
- All Turbulent Flow
- Surface Finish - Smooth Paint
- Sustainer (Stage-2) Ignition Delay Adjusted to Match Flight Data
- Launch Angle from Vertical = 2.77 deg, Adjusted to Match Downrange Distance at Apogee from GPS Data of 55,767 ft
Altitude (ft)
Time (sec)
350000
300000
250000
200000
150000
100000
50000
0
0
20
40
60
80
100
120
140
160
180


MESOS 293K ft Flight - Postflight RASAero II Simulation - Velocity Versus Time
RASAero II Flight Simulation
- No Wind
- All Turbulent Flow
- Surface Finish - Smooth Paint
- Sustainer (Stage-2) Ignition Delay Adjusted to Match Flight Data
- Launch Angle from Vertical = 2.77 deg, Adjusted to Match Downrange Distance at Apogee from GPS Data of 55,767 ft
Accelerometer-Based Velocity
GPS-Based Velocity
RASAero II Flight Simulation
Accelerometer-Based Maximum Velocity = 4,047 ft/sec (Mach 4.18)
RASAero II Maximum Velocity = 4,095 ft/sec (Mach 4.23)
(+1.19% Error)
Velocity (ft/sec)
Time (sec)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
0
20
40
60
80
100
120
140
160
180

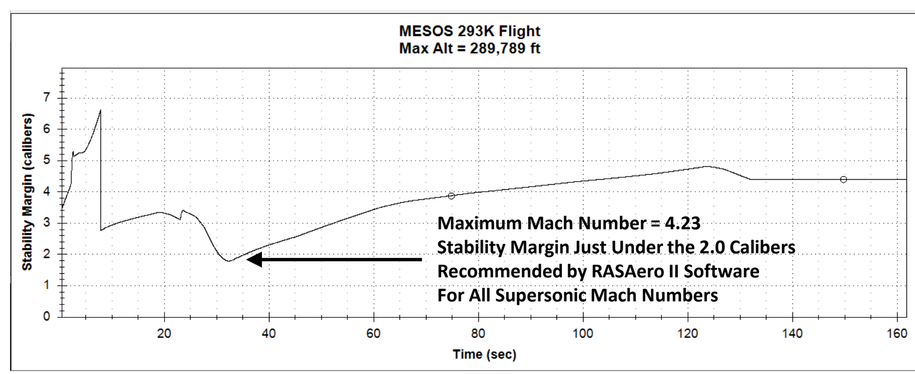








- **Sustainer (Stage-2) Stability Margin**
  - **Sustainer Stability Margin at Maximum Mach Number (Mach 4.23) Just Under the 2.0 Calibers Stability Margin Recommended by the RASAero II Software**
- **2.0 Calibers Stability Margin Recommended for All Supersonic Mach Numbers**
- **Rocket Flown Successfully**



How RASAero II Varies Thrust with Altitude

- Method Used in RASAero II to Vary Thrust with Altitude
  - Equation for Thrust for Solid Rocket Motors and Liquid Rocket Engines (Conical Nozzle)

$$F_\alpha = \lambda(\dot{m}V_e + (p_e - p_\infty)A_e)$$

Where:
- F_α = thrust corrected for altitude and nozzle divergence
- λ = $1/2\,(1 + \cos(\alpha))$
- α = nozzle divergence half-angle measured at the nozzle exit
- $\dot{m}$ = nozzle mass flow rate
- V_e = nozzle exit velocity
- p_e = nozzle exit pressure
- p_∞ = atmospheric pressure
- A_e = nozzle exit area

$$\dot{m} = A_{th}\, p_c \left\{\gamma \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}} \frac{M_f}{RT_c}\right\}^{\frac{1}{2}}$$

$$V_e = \sqrt{\frac{2\gamma}{(\gamma-1)} \frac{RT_c}{M_f}\left[1 - \left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

- M_f = **Molecular weight of gas**
- p_c = **chamber pressure**
- R = **universal gas constant**
- T_c = **chamber temperature**
- γ = **ratio of specific heats**

  - Nozzle Mass Flow ($\dot{m}$) Not a Function of Atmospheric Pressure (p_∞), Does Not Vary with Altitude
  - Exhaust Velocity (V_e) Not a Function of Atmospheric Pressure, Does Not Vary with Altitude
  - Divergence Angle Correction (λ) Does Not Change with Altitude, Applies Equally at All Altitudes
  - Pressure Differential on Nozzle Exit Area [$(p_e - p_\infty)A_e$] Varies Thrust with Altitude

How RASAero II Varies Thrust with Altitude (Cont'd)

- Method Used in RASAero II to Vary Thrust with Altitude (Cont'd)
  - Nozzle Exit Pressure (p_e) a Function of Chamber Pressure (p_c) and Nozzle Expansion Ratio (ϵ)

$$\epsilon = \frac{A_e}{A_{th}} = \frac{\left(\frac{\gamma-1}{2}\right)^{\frac{1}{2}} \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}}{\left(\frac{p_e}{p_c}\right)^{1/\gamma} \left[1 - \left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right]^{\frac{1}{2}}}$$

  - If Chamber Pressure Time History Stays the Same, and Any Nozzle Throat Erosion with Time (Any Variation in the Nozzle Expansion Ratio with Time) Stays the Same, Then the Nozzle Exit Pressure Time History will Stay the Same, Even with Changes in Altitude
  - If the Nozzle Exit Pressure Time History Stays the Same, Then the Change in Thrust with Altitude Will Be The Change in Atmospheric Pressure Applied to the Nozzle Exit Area

How RASAero II Varies Thrust with Altitude (Concl'd)

- Method Used in RASAero II to Vary Thrust with Altitude (Cont'd)

$$F_\alpha = F_{ref} + (p_{\infty_{ref}} - p_\infty) A_e$$

Where: F_α = thrust corrected for altitude and nozzle divergence

F_{ref} = thrust at reference altitude condition

p_∞ = atmospheric pressure

$p_{\infty_{ref}}$ = atmospheric pressure at reference altitude condition

- In RASAero II Software:
  - rasp.eng Motor Data is the Thrust at Reference Altitude Condition
  - Atmospheric Pressure at Reference Altitude Condition is Assumed to be Sea Level Atmospheric Pressure
    - rasp.eng Motor Data is Assumed to be a Sea Level Thrust Curve
  - Thrust is Then Varied with Altitude in RASAero II Flight Simulation Using an Atmospheric Pressure with Altitude Model Anchored to Launch Site Atmospheric Conditions
  - Nozzle Exit Diameter Input for Nozzle Exit Area is Not Only Used for Power-On Drag Coefficient (CD) Model, It Is Also Used for Thrust with Altitude (A_e in Equation Above)

Increased Nozzle Expansion Ratio Used on Sustainer Stage (Stage-2) of MESOS Rocket

- Kip Daugirdas Planned to Use an Increased Nozzle Expansion Ratio on the MESOS Rocket Sustainer Stage (Stage-2) for Increased Performance at Altitude
- Original Sustainer Stage Motor had Been Static Fired at 5,000 ft Elevation with Low Expansion Ratio Nozzle
- To Help Assess Performance Benefit Chuck Rogers Backed-Out Chamber Pressure Time History from the Thrust Data from the 5,000 ft Elevation Static Firing, Then Created a New Sea Level Thrust Curve for the Motor with a High Expansion Ratio Nozzle
  - Used Techniques from “Departures from Ideal Performance” Technical Article in Technical Report Downloads – Solid Rocket Motor Section on RASAero Web Site
  - Note Chamber Pressure in Previously Presented Equations is Nozzle Stagnation (Total) Pressure, the Stagnation (Total) Pressure Entering the Nozzle. It is Not the Pressure Measured at the Head End of the Motor, Which Needs to Be Corrected to Obtain Chamber Pressure. (See “Departures from Ideal Performance”.)
  - New Thrust Curve Converted to rasp.eng Motor Data Format
  - Motor Never Actually Static Fired with New High Expansion Ratio Nozzle, New Thrust Curve was Based on Analysis, Not An Actual Static Firing
- New rasp.eng Thrust Curve Data with High Expansion Ratio Nozzle at Sea Level, Along with New Nozzle Exit Area, Could Then Be Used to Run RASAero II Flight Simulation
  - Thrust Automatically Varied with Altitude in RASAero II Flight Simulation

Increase in Performance from Increased Nozzle Expansion Ratio on Sustainer Stage (Stage-2) of MESOS Rocket

RASAero II Flight Simulations
- **No Wind**
- **All Turbulent Flow**
- **Surface Finish - Smooth Paint**
- **Sustainer (Stage-2) Ignition Delay Adjusted to Match Flight Data**
- **Launch Angle from Vertical = 2.77 deg**

Low Expansion Ratio Nozzle
Nozzle Expansion Ratio = 6.5025

Sustainer Motor Ignition = 33,944 ft AGL
Sustainer Motor Burnout = 61,505 ft AGL
Maximum Velocity = 3,834 ft/sec

RASAero II
Predicted Apogee Altitude = 257,248 ft

AGL = Above Ground Level

High Expansion Ratio Nozzle
Nozzle Expansion Ratio = 12.84
(As Flown on Flight)

Sustainer Motor Ignition = 33,944 ft AGL
Sustainer Motor Burnout = 62,471 ft AGL
Maximum Velocity = 4,095 ft/sec

RASAero II
Predicted Apogee Altitude = 289,789 ft
GPS Apogee Altitude
(Actual Flight) = 293,488 ft

Increased Nozzle Expansion Ratio
on Sustainer Stage (Stage-2)
Increased Apogee Altitude
by Approximately 30,000 ft

Summary

- Original MESOS Apogee Altitude Prediction Would Have Been Expected to be Approximately 230,000 ft
- Using High Expansion Ratio Nozzle on Sustainer Stage (Stage-2) Increased Apogee Altitude by Approximately 30,000 ft
- Surface Finish After Mach 4 Aerodynamic Heating Being More Accurately Modeled by Smooth Paint Rather Than Rough Camouflage Paint Increased Apogee Altitude by Approximately 10% (Approximately 30,000 ft)
- MESOS Rocket Reached a GPS Measured Apogee Altitude of 293,488 ft Above Ground Level, 297,398 ft Above Sea Level
  - Rocket Reached 90% of the Altitude to the Karman Line = 100 km = 328,084 ft Above Sea Level (Definition of the Beginning of Space)