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Small UAV Conceptual Designs by NASA LaRC

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Project Reimar

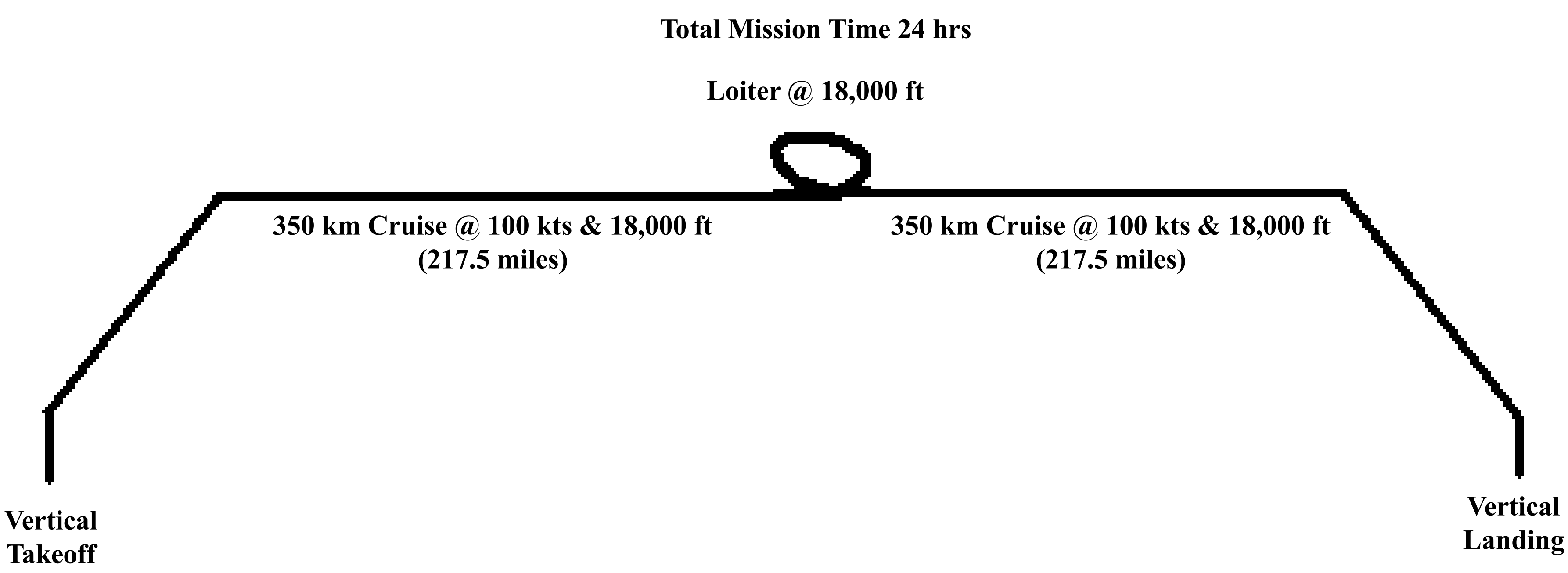
Requirements

AERONAUTICS

- Transportation
  - Ford F150 size truck to transport everything
- Science Payload
  - 25 lbs
- SatComm Payload
  - Min 5Mbps – 35 lbs
- VTOL
- 24 hr Mission Endurance
- 100 kt Dash Speed
- 18,000 ft Ceiling
- 20 ft wingspan

Aeromech Fury
12 ft Span
115 lb MTOW

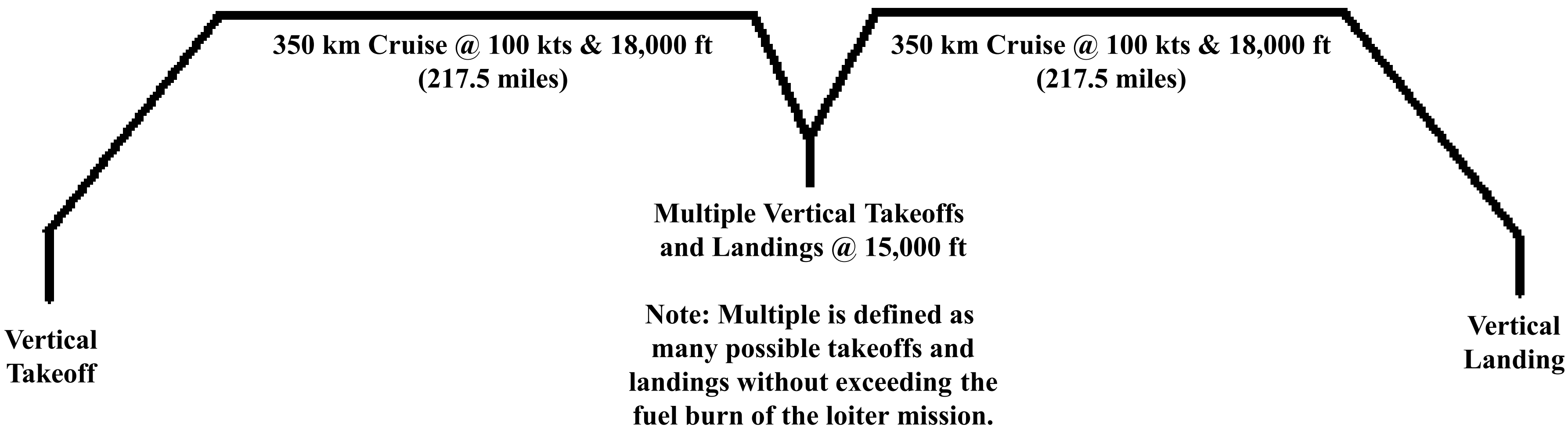
Requirements - Primary Mission



Requirements - Sensor Placement Mission

Alternate Non-Sizing Mission

Rate of Climb (ROC) decreased to avoid sensor placement mission resulting in vehicle re-sizing
Vertical ROC at sea level = 200 ft/min, Vertical ROC at 15,000 ft = 100 ft/min
Climb Horizontal ROC = 500 ft/min in both missions



Design Strategy

- Attempt to match hover power to cruise power
  - Reduce hover sizing penalties
    - Reduced engine size reduces MTOW
  - Maximize Cruise efficiency
    - Preventing throttle losses at low power operation
      - Does not apply to compression ignition engines
- Low disk loading
  - High solidity
    - Low tip speed
      - Low Noise
- Fast Assembly
  - Vehicle small enough to be carried in a pickup truck
  - Minimal number of components that need to be assembled to ready the vehicle for flight

Tazenflugel Introduction

- Name
  - Spinning Wings (German)
  - Tasmanian Devil (Looney Tunes)
- Description
  - Tail sitter
  - Wings spin as rotor for vertical flight
  - Props are at similar advance ratio horizontal flight as in hover
- Hover Control (Body Axis)
  - Pitch & Yaw via swashplateless technology like “Heliflap”. Aileron is deflected as a function of rotation angle to generate moments.
  - Roll via tail mounted control surfaces
    - Limited control power due to low dynamic pressure of rotor wash.
    - Minimal control requirement about this axis. Only need to counter friction of main bearing.
      - Could use a small electric motor on bearing to counteract friction to further reduce control requirement if necessary

Dos Samara Introduction

- Name
  - Samara Seed
  - Dos → Two (Spanish)

- Description
  - Outer wing panels function as single blade rotors for vertical flight.
  - Pusher propeller provides thrust for cruise
  - No tip over issues
  - No SatComm field of view issues
  - Easier payload integration
- Hover Control
  - Pitch via swashplateless technology like "Heliflap". Aileron is deflected as a function of rotation angle to generate moments.
  - Roll via swashplateless technology like "Heliflap". Aileron is deflected uniformly on the rotor to provide a collective type response for each rotor.
  - Yaw via pusher prop gimbals side to side to vector thrust

Animation

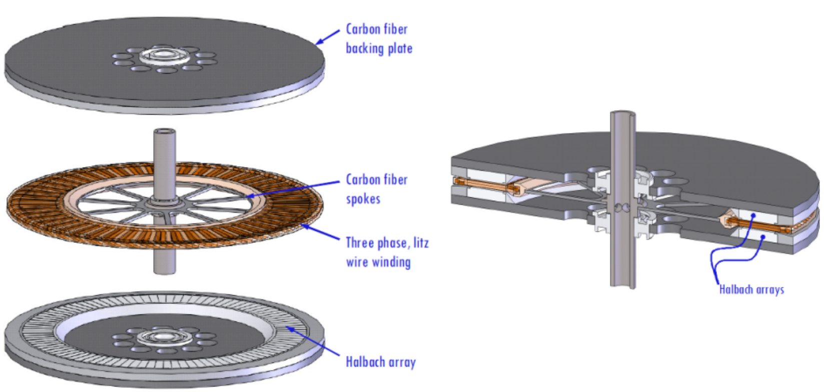
Electric Technologies

Motors

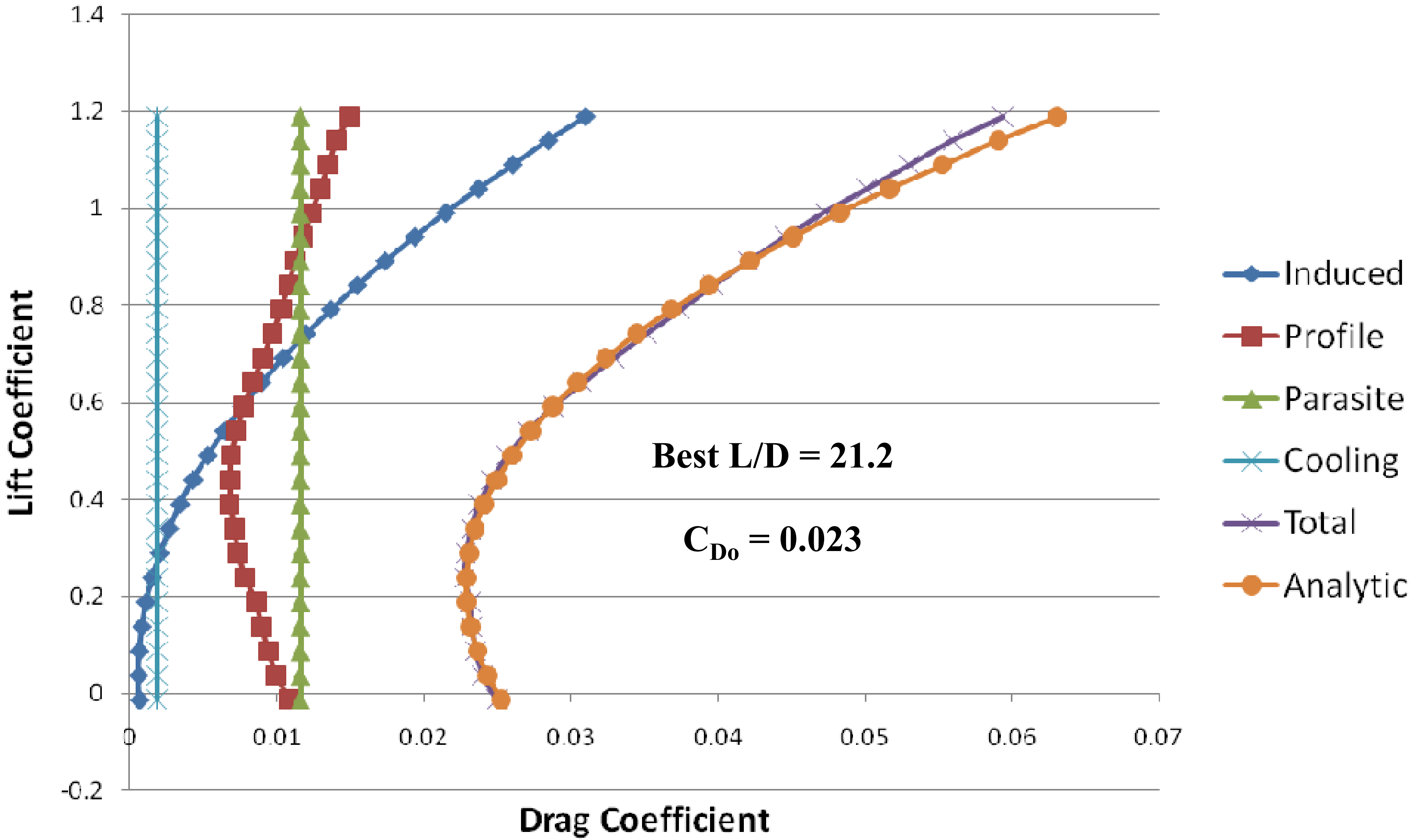
- Launchpoint Halbach Array Motor (ironless with field located on one side)
  - 7 hp @ 8400 rpm
  - 1.4 lbs (5 hp/lb)
  - 95% peak efficiency
  - 6” diameter

Batteries

- Sion Lithium Sulfur
  - Highest demonstrated rechargable energy density
  - Demo on QinetiQ Zephyr high altitude UAV (2007)
  - 576 cells, each cell achieving 350 Whr/kg
  - Limited recharge cycles



Dos Samara Drag Polar



Note: This polar is trimmed at a C_L of 0.4

Dos Samara

AERONAUTICS

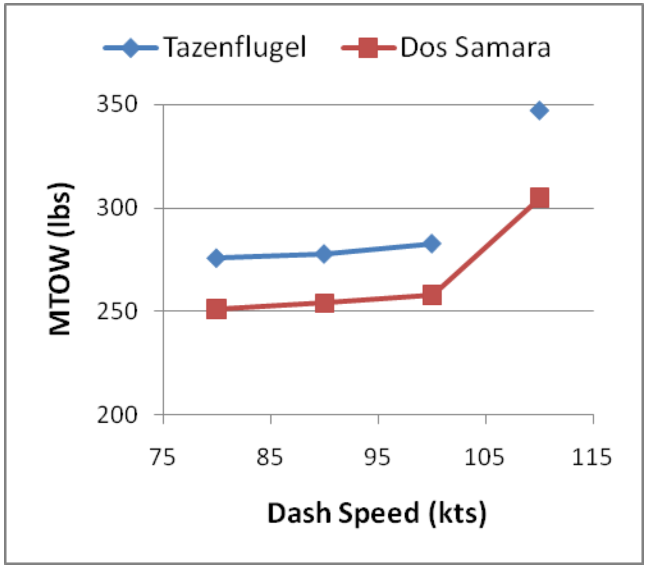
MTOW	258 lbs
Wing Loading	10 lbs/ft^2
Wing Area	25.8 ft^2
Wing Span	19.7 ft
Aspect Ratio	15.00
Best L/D Ratio	21.52
CL for Best L/D	0.79
Engine Power Loading	37 lbs/hp
Engine Power	7.0 hp

Sensitivities

- Requirements
- Sizing
- Technology Level

Dash Speed

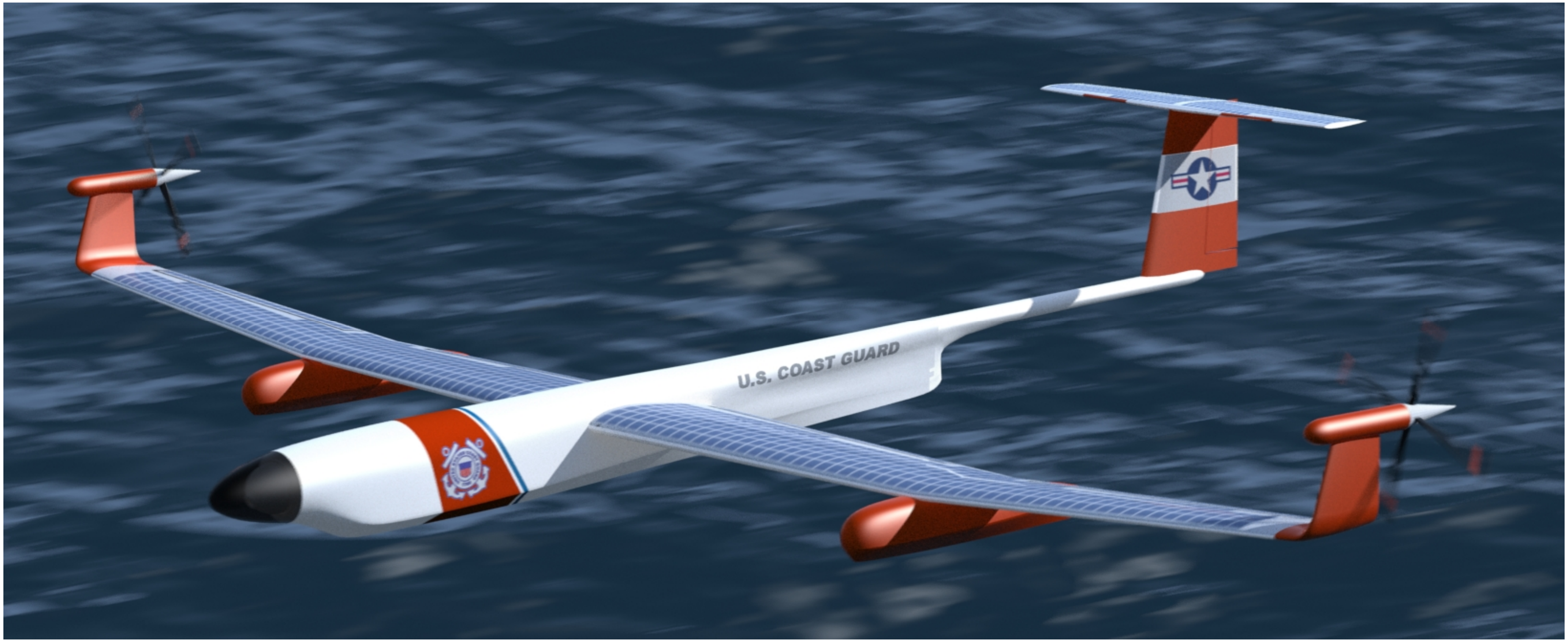
Dash Speed (kts)	Tazenflugel MTOW (lbs)	Dos Samara MTOW (lbs)
110	*347*	305
100	283	258
90	278	254
80	276	251



Notes:

- Tazenflugel 110 kt dash did not converge and correlates to 38.7% airframe weight
- If the span constraint was relaxed to 21 ft, Tazenflugel would converge with the 110 kt dash speed at MTOW of 306 lbs

Persistent Open Ocean Aircraft



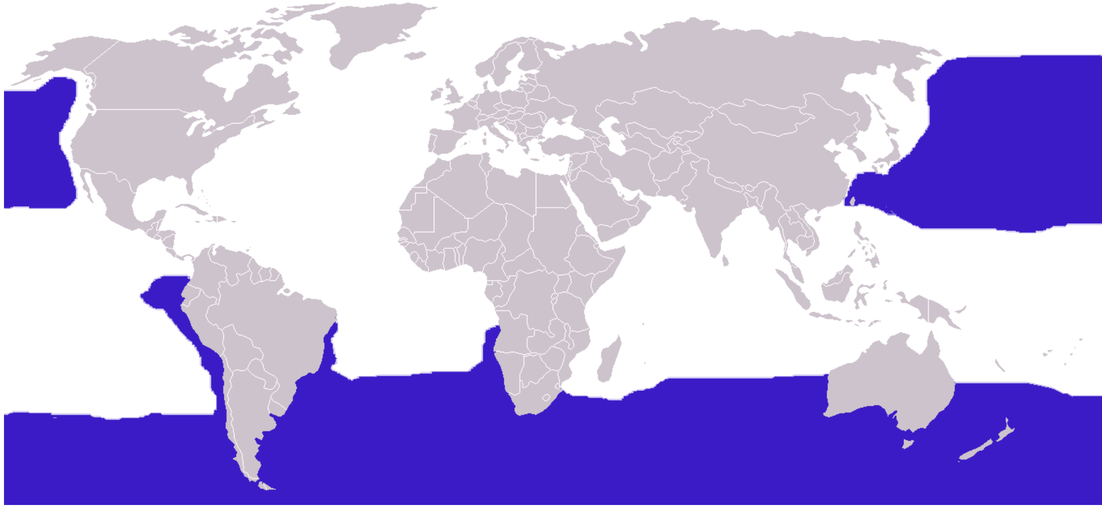
Albatross

Two well known naturalists:

"The albatross can maintain this swooping soaring flight for hours on end without a single wing beat."
- David Attenborough

"The albatross … manages to remain master of its own course, either being carried all the way around the globe or, on the contrary, making way against the strong winds without a beat of its wings."
- Jacques Cousteau

- Can travel over 1000 km/day
- Locks out its shoulder joint
- Can sleep while flying
- Circumnavigating Antarctica several (~6) times in a year searching for food
  - Primarily Squid



How Flies the Albatross - the Flight Mechanics of Dynamic Soaring **SAE 2004-01-3088 by J. Philip Barnes**

Albatross Specifics

- 24 lbs
- 11.5 ft Span
  - Largest wing span of any bird
- AR 16 wing
- Best L/D = 27
  - We as humans can't build higher L/D vehicle of this size class due to Reynolds Number effects.
- It can do all of this with:
  - Extreme STOL
  - Water Takeoff and Landing
  - Folding Wings
  - Flies so easily they even nap while flying

How Flies the Albatross - the Flight Mechanics of Dynamic Soaring **SAE 2004-01-3088 by J. Philip Barnes**

Dynamic Soaring Introduction

Dynamic Soaring Characteristics

- Maneuver Duration: 2 to 15 seconds
- Climb Into Wind: Airspeed drops slower than inertial velocity
- Turn Down Wind: Gain inertial velocity
- Descend with Tailwind: Trade high inertial velocity for airspeed
- Lower Turn: coast to where you want to go next until repeating the maneuver
- Need high L/D at 1g to 5g conditions
- Probably need short duration thrust to overcome low energy state situations, which will not impact normal soaring drag

Dynamic Soaring Methods

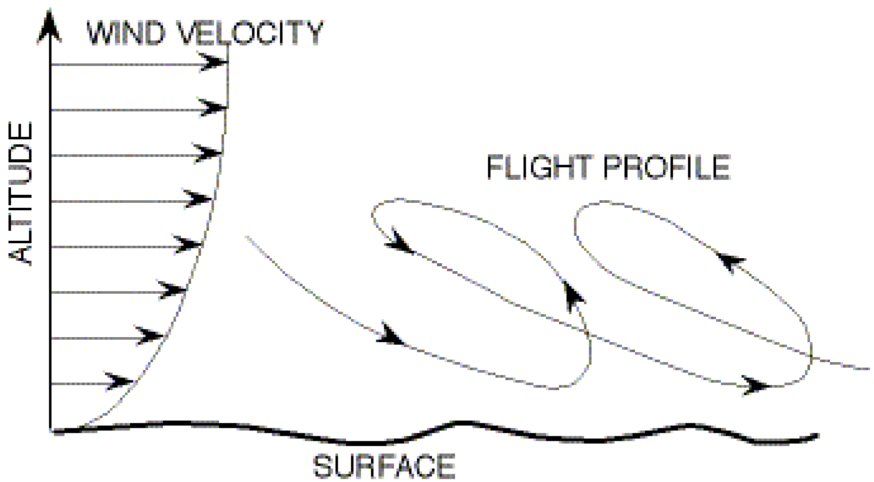
Boundary Layer

- Wind is blowing faster at altitude than near the surface

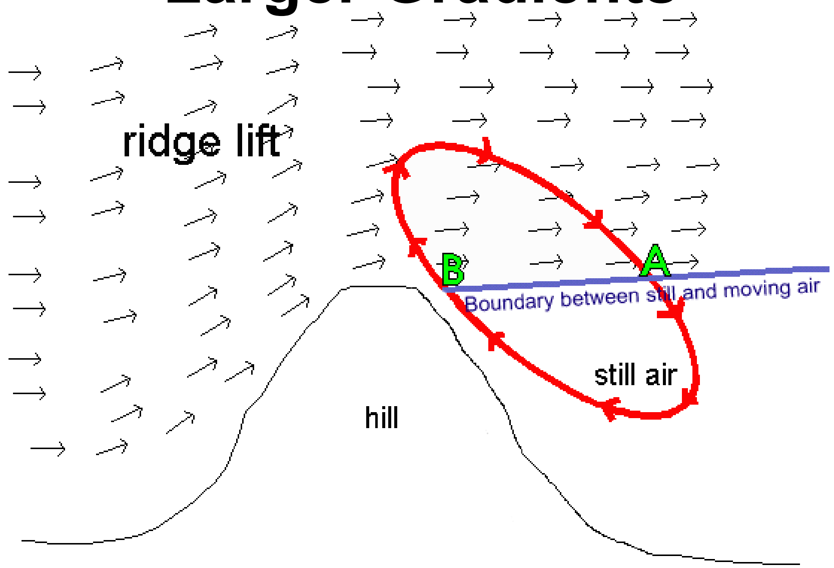
Terrain Interaction

- Lee side of a ridge line
- Air separates at the crest of the ridge
- Air below the ridge is moving slower then the air above the ridge line

Smaller Gradients

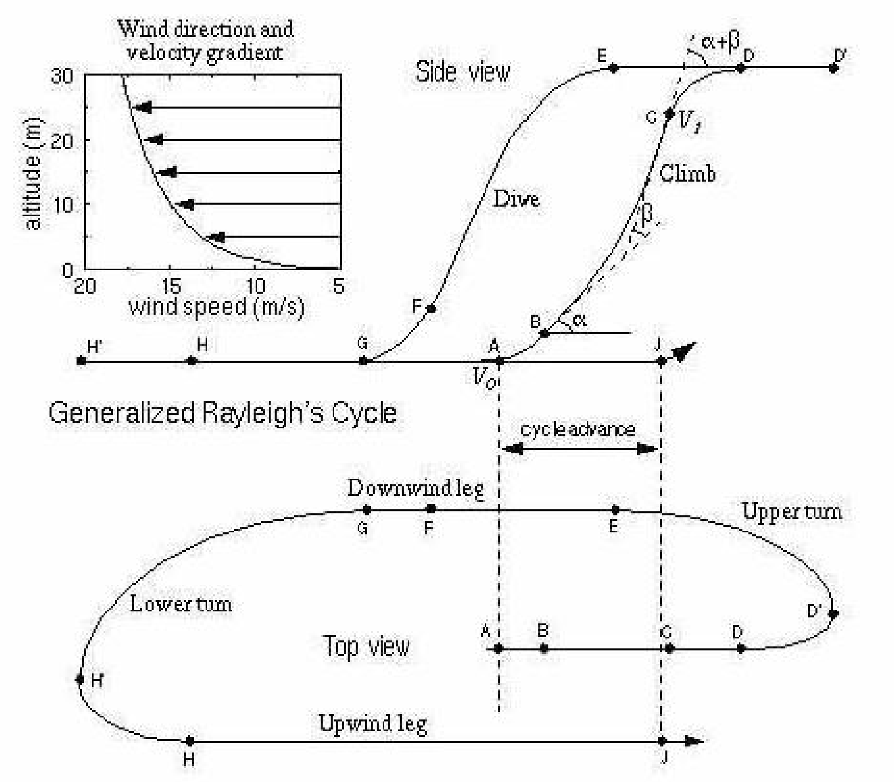


Larger Gradients



Dynamic Soaring Trajectory

- Velocity gradient is key
  - Stronger gradient means easier to extract energy.
- Climb into the wind
- Descend with a tailwind



Prior Effort

- US Air Force & NASA Dryden Flight Research Center
  - Randel J. Gordon, Capt. USAF *"Optimal Dynamic Soaring For Full Size Sailplanes"* September 2006
  - Focused on the L-23 Super Blanik
    - In production aluminum 2 seat trainer
  - Point Mass Trajectory Optimization (Matlab)
  - 6 DOF Flight Simulator (Large Amplitude Multi-Mode Aerospace Research Simulator (LAMARS) Wright-Patterson AFB)
    - Feasibility of piloting hair-pin maneuvers
  - 6 DOF Flight Simulator (APEX Simulator NASA Dryden)
    - Developed DynaSoar 3.0 pilot display for flight testing
  - Full Scale Flight Testing (NASA Dryden)
    - Used the wind velocity as a function of altitude only (no surface interaction)
- Sandia National Laboratories
  - Mark B.E. Boslough *"Autonomous Dynamic Soaring Platform for Distributed Mobile Sensor Arrays"* June 2002
  - Focused on a 8' span model of a Schweizer SGS 1-36 sailplane
  - 6 DOF Model (LaRCsim NASA Langley)
  - 6 DOF Flight Simulator (FlightGear Open Source)
    - Incorporates graphics and pilot in the loop option
    - Uses LaRCsim Flight Dynamics Model
  - 6 DOF Flight Simulator (JSBSim Open Source)
    - Replaces LaRCsim as the Flight Dymamics Model
  - Flight Testing of RC 8' span foam model
    - Used the shear on the lee side of a ridge

Dynamic Soaring

AERONAUTICS

$$P_S = -\frac{DV_t}{mg} - \left[\frac{WIND_{SLOPE} \sin(\gamma)\cos(\gamma)\sin(\psi)V_t^2}{g} \right]$$

- Excess power can be positive if the Dynamic Soaring Term (DST) outweighs the Energy Loss Due to Drag term.

Note:

- sin(Ψ) is negative when heading westbound.
  - The wind is from the west in this derivation.
- cos(γ) is negative when descending

Where:

- P_S – Specific Excess Power (ft/sec)
- D – Drag (lbs)
- V_t – True Airspeed (ft/sec)
- m – Mass (lb_m)
- g – Gravitational Acceleration (ft/sec^2)
- $WIND_{SLOPE}$ -- change in wind speed with altitude (ft/sec/ft)
- γ – Flight Path Angle (deg)
- Ψ – Heading Angle (deg)

Reference: Gordon, USAF *OPTIMAL DYNAMIC SOARING FOR FULL SIZE SAILPLANES.*

Equation Example

$$P_S = -\frac{DV_t}{mg} - \left[\frac{WIND_{SLOPE} \sin(\gamma)\cos(\gamma)\sin(\Psi)V_t^2}{g} \right]$$

Example Data:

- 100 lb (3.1 slugs) Aircraft
- 60 kts (101 ft/s) Velocity
- 40:1 L/D
- .08 ft/s/ft Wind Gradient
- +/-25^0 (+/-.436 radians) climb or descent
- 270^0 or 90^0 (4.71 or 1.57 rad) Heading

Example 1 – Climbing to the West

$$P_S = -\frac{2.5*101}{3.1*32.2} - \left[\frac{.08*\sin(.436)\cos(.436)\sin(4.71)*101^2}{32.2} \right]$$

$$P_S = -2.53 - [-9.69] = 7.16\frac{ft}{s}$$

Example 2 – Descending to the East

$$P_S = -\frac{2.5*101}{3.1*32.2} - \left[\frac{.08*\sin(-.436)\cos(-.436)\sin(1.57)*101^2}{32.2} \right]$$

$$P_S = -2.53 - [-9.69] = 7.16\frac{ft}{s}$$

Example 3 – Climbing to the East

$$P_S = -\frac{2.5*101}{3.1*32.2} - \left[\frac{.08*\sin(.436)\cos(.436)\sin(1.57)*101^2}{32.2} \right]$$

$$P_S = -2.53 - [9.69] = -12.22\frac{ft}{s}$$

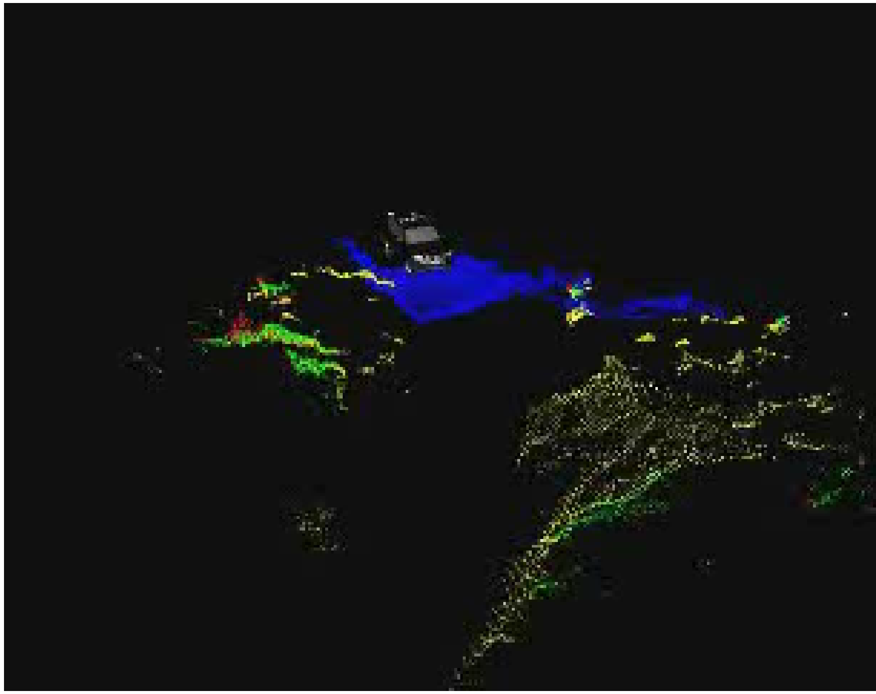
Example 2 – Descending to the West

$$P_S = -\frac{2.5*101}{3.1*32.2} - \left[\frac{.08*\sin(-.436)\cos(-.436)\sin(4.71)*101^2}{32.2} \right]$$

$$P_S = -2.53 - [9.69] = -12.22\frac{ft}{s}$$


U.S. COAST GUARD

CONOP Barriers



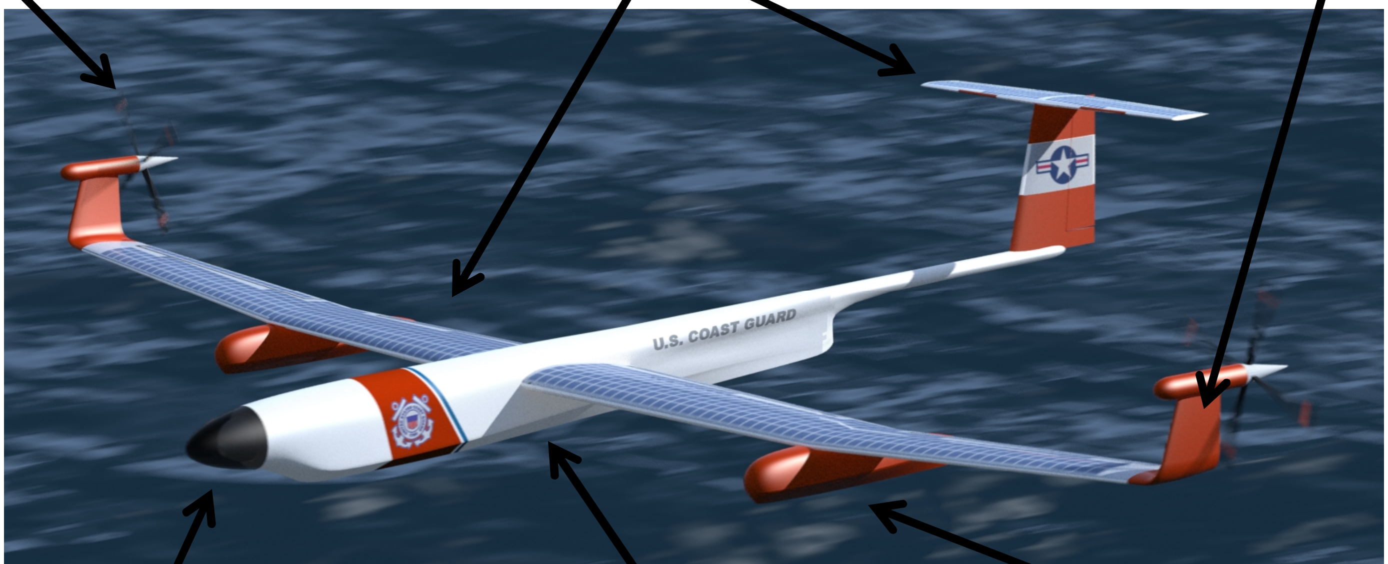
- Instantaneous wave mapping
  - Water is a more difficult LIDAR target than soil
- Control Systems
  - Autonomous control system
  - Predictive maneuver logic
  - High rate sensors (gyros can't "tumble" during maneuver)
- Reliability of staying airborne
  - Development and testing of DS maneuver in realistic wind gradients
- Reliability of water takeoff and landings
  - When wind has died must land on surface like the Albatross
- Satellite communication energy required

Design Features

Tip Turbines to extract energy or provide thrust

Solar Cells to power electronics during calm days when aircraft is not flying

Tip turbines on winglets to remain clear of water when landing



Payload

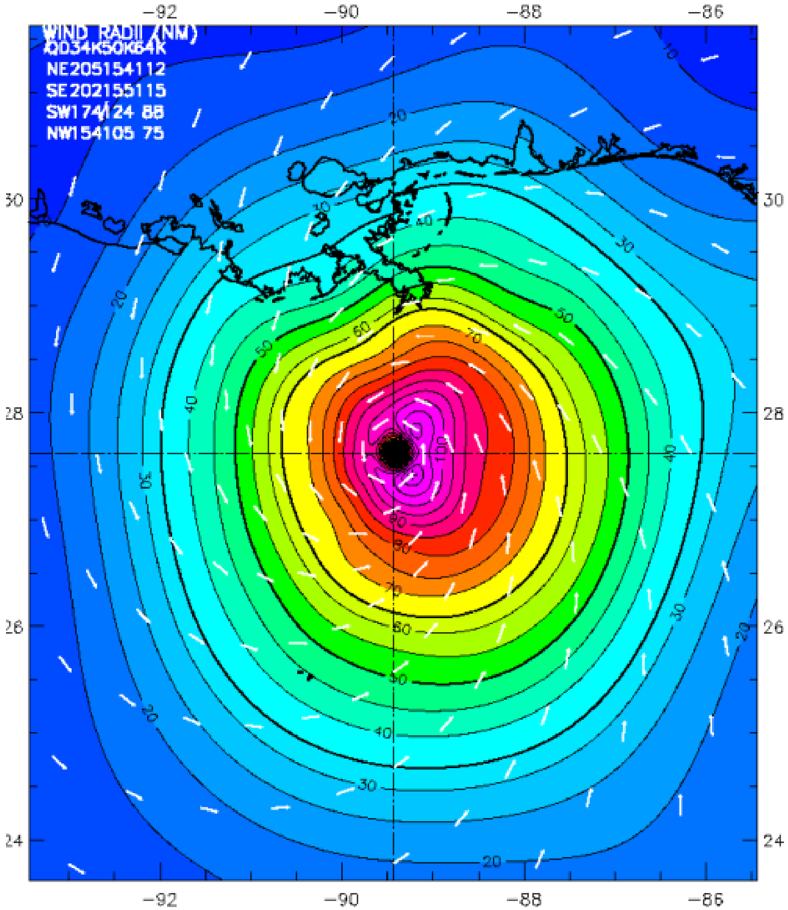
Low drag boat hull (no step in hull)

Span loaded batteries inside floats

Mission Applications

- Potential applications for an ocean-based dynamic soaring vehicle.
  - Global warming data through highly distributed sampling (with dynamically allocatable resources)
  - Weather reporting
  - Sea life monitoring
  - Fishery observation and enforcement
  - Surveillance/Observation
  - Search and Rescue

Prior Effort Analysis



Low Altitude Hurricane Penetrator Vehicle Concept

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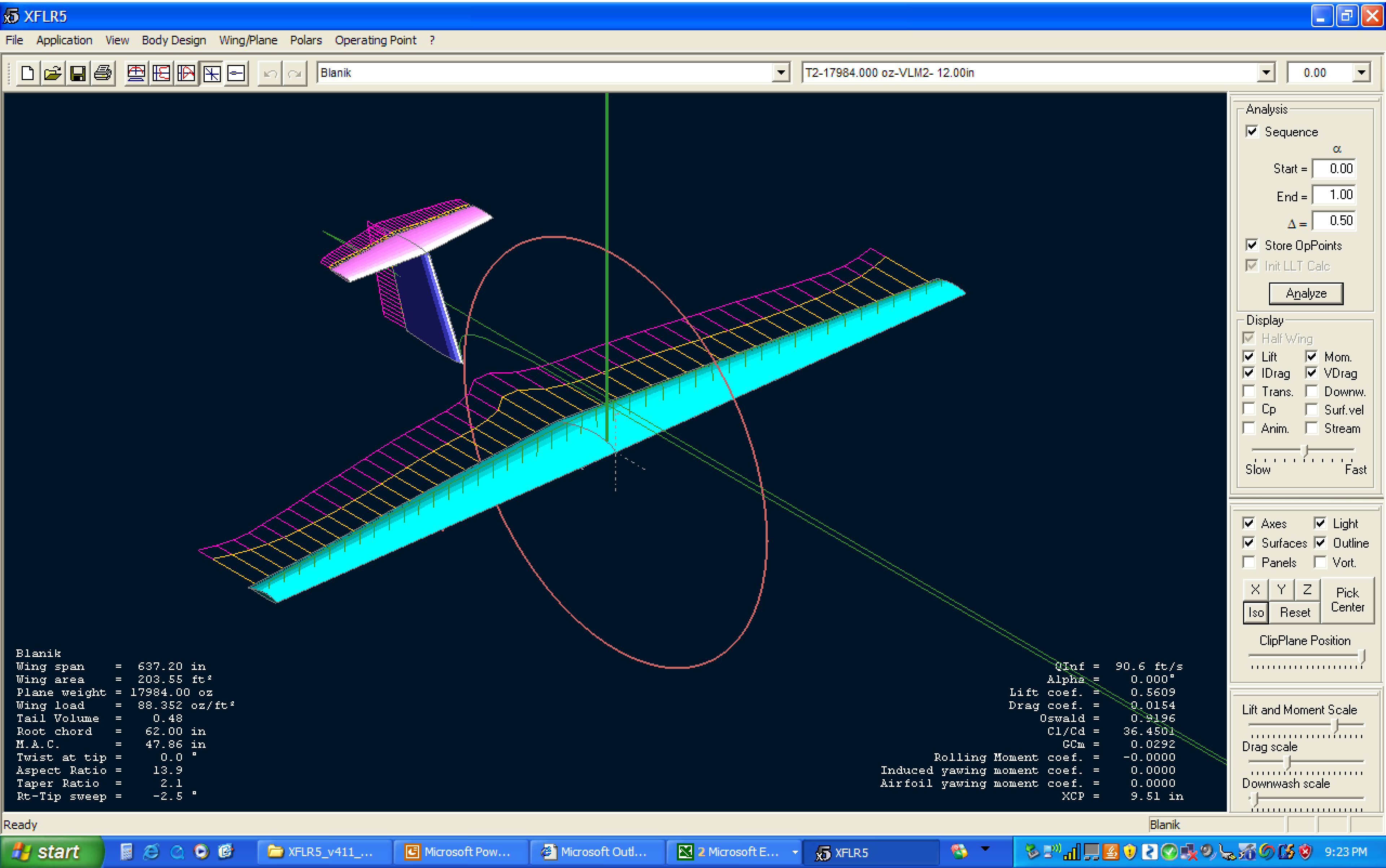
November 21, 2008

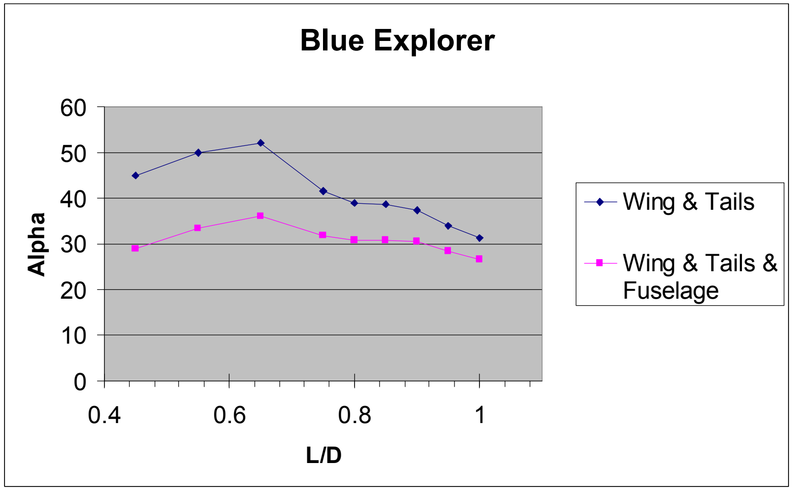
XFLR5

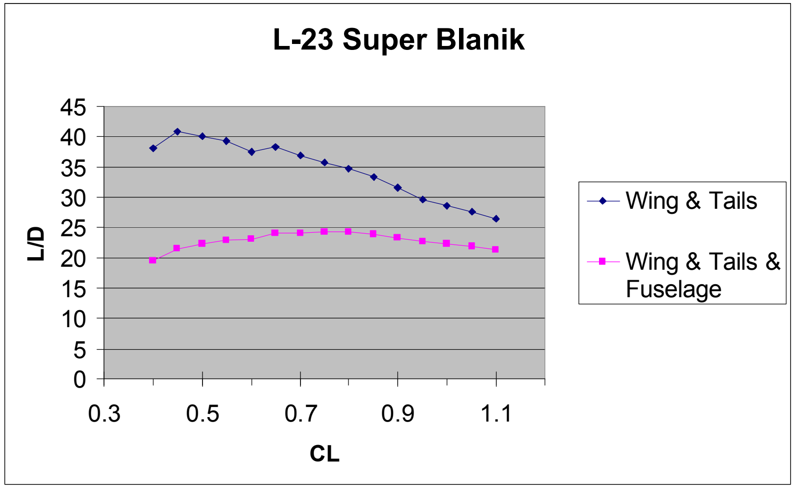

XFLR5
File Application View Body Design Wing/Plane Polars Operating Point ?
Blanik
T2-17984.000 oz-VLM2- 12.00in
0.00
Analysis
Sequence
α
Start = 0.00
End = 1.00
Δ = 0.50
Store OpPoints
Init LLT Calc
Analyze
Display
Half Wing
Lift
Mom.
IDrag
VDrag
Trans.
Downw.
Cp
Surf.vel
Anim.
Stream
Slow
Fast
Axes
Light
Surfaces
Outline
Panels
Vort.
X Y Z
Iso
Reset
Pick Center
ClipPlane Position
Lift and Moment Scale
Drag scale
Downwash scale
Blanik
Wing span = 637.20 in
Wing area = 203.55 ft²
Plane weight = 17984.00 oz
Wing load = 88.352 oz/ft²
Tail Volume = 0.48
Root chord = 62.00 in
M.A.C. = 47.86 in
Twist at tip = 0.0 °
Aspect Ratio = 13.9
Taper Ratio = 2.1
Rt-Tip sweep = -2.5 °
QInf = 90.6 ft/s
Alpha = 0.000°
Lift coef. = 0.5609
Drag coef. = 0.0154
Oswald = 0.9196
Cl/Cd = 36.4501
GCm = 0.0292
Rolling Moment coef. = -0.0000
Induced yawing moment coef. = 0.0000
Airfoil yawing moment coef. = 0.0000
XCP = 9.51 in
Ready
Blanik
start
XFLR5_v411_...
Microsoft Pow...
Microsoft Outl...
2 Microsoft E...
XFLR5
9:23 PM

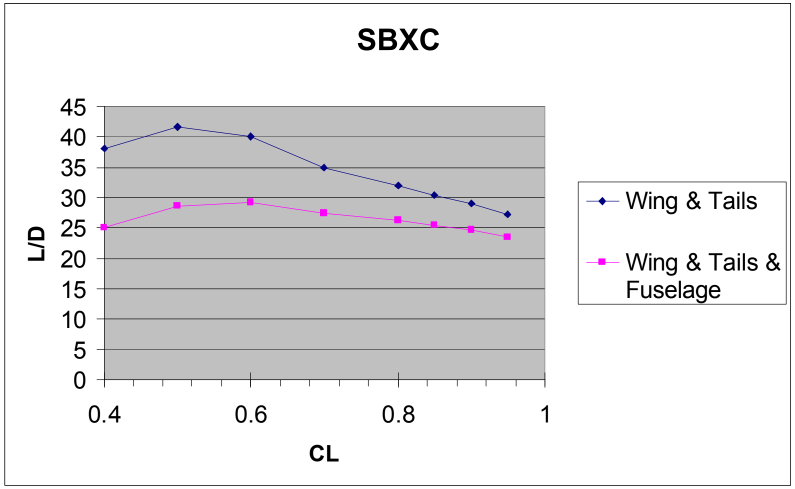
Aerodynamic Models

AERONAUTICS

- **Blue Explorer**
    - Root Re #: 1,000,000
    - Tip Re #: 500,000
- **SBXC**
    - Root Re #: 700,000
    - Tip Re #: 200,000
- **L-23 Super Blanik**
    - Root Re #: 5,000,000
    - Tip Re #: 2,000,000







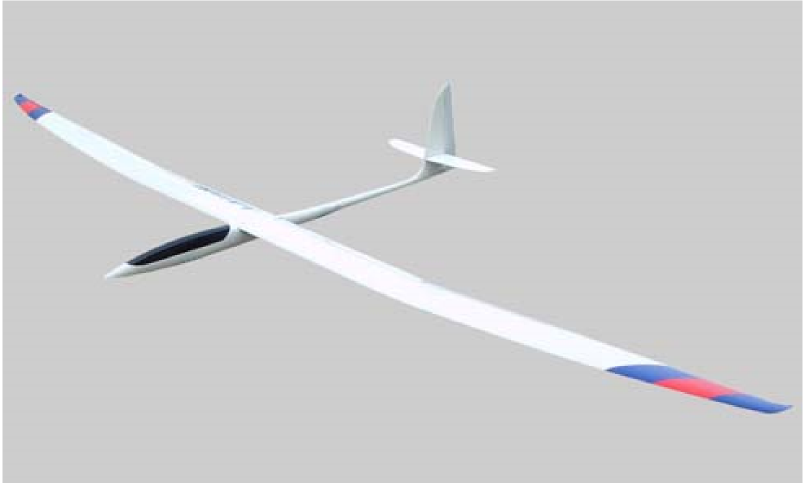
Trajectory Analysis

- Computes energy state at each time step
- Integrates energy around the trajectory path
- Useful for:
  - Determining the required wind gradient to maintain flight
  - Determining the approximate L/D for a given wind gradient
- Limitations:
  - Can not determine optimal trajectory path (must be specified)
  - Gamma and psi are specified as a function of time (Air Force/DFRC paper)
  - Starting velocity must match gamma and psi initial conditions

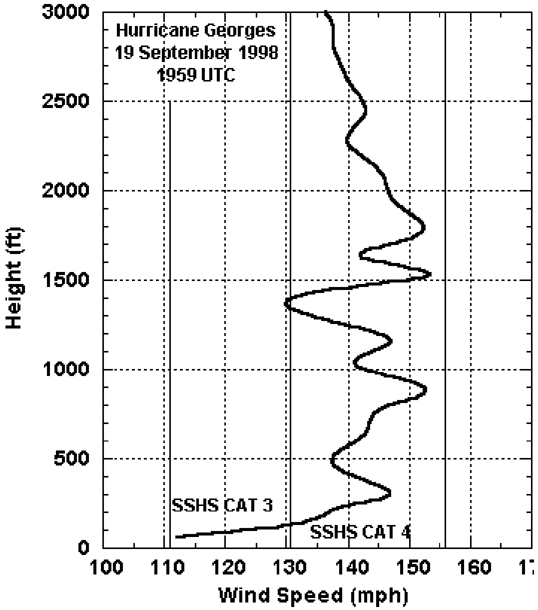
Required Wind Gradients

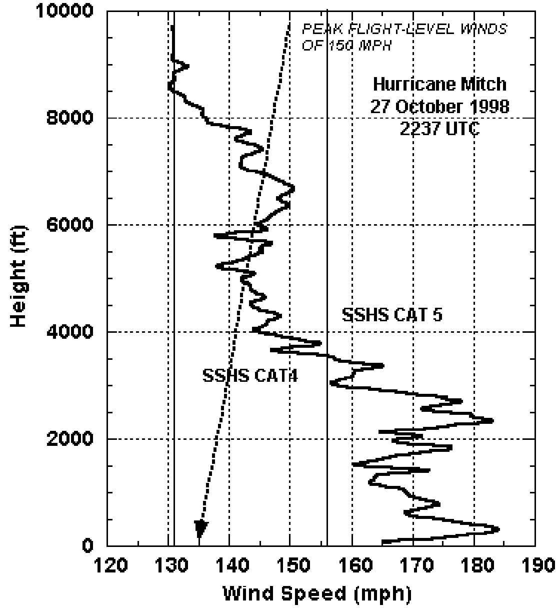
AERONAUTICS

- Blue Explorer
  - **Wing Span:** 18.2 ft
  - **Wing Area:** 13.6 ft^2
  - **Aspect Ratio:** 24.3
  - **Wing Loading:** 5.3 lbs/ft^2
  - **Airfoil:** HQW 2.5-spec
  - **L/D Max:** 36 @ Root Re# 1,000,000
    28 @ Root Re# 500,000
  - **Required Gradient:** 3.9 kts/100ft
- SBXC
  - **Wing Span:** 14.2 ft
  - **Wing Area:** 10.7 ft^2
  - **Aspect Ratio:** 19.8:1
  - **Wing Loading:** 5.3 oz./sq. ft
  - **Airfoil:** SD-2048
  - **L/D Max:** 29 @ Root Re# 700,000
    24 @ Root Re# 300,000
  - **Required Gradient:** 4.8 kts/100 ft



Hurricane Environment





Reference: http://www.nhc.noaa.gov/aboutwindprofile.shtml#hock1999

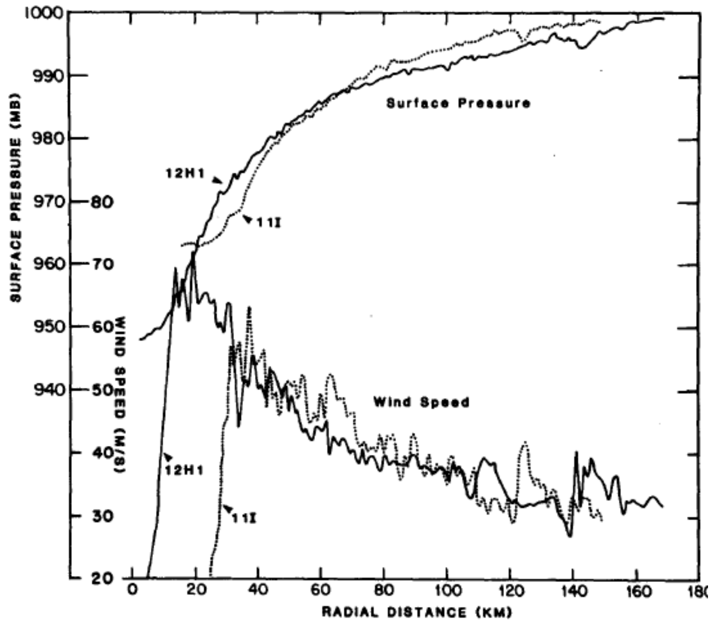
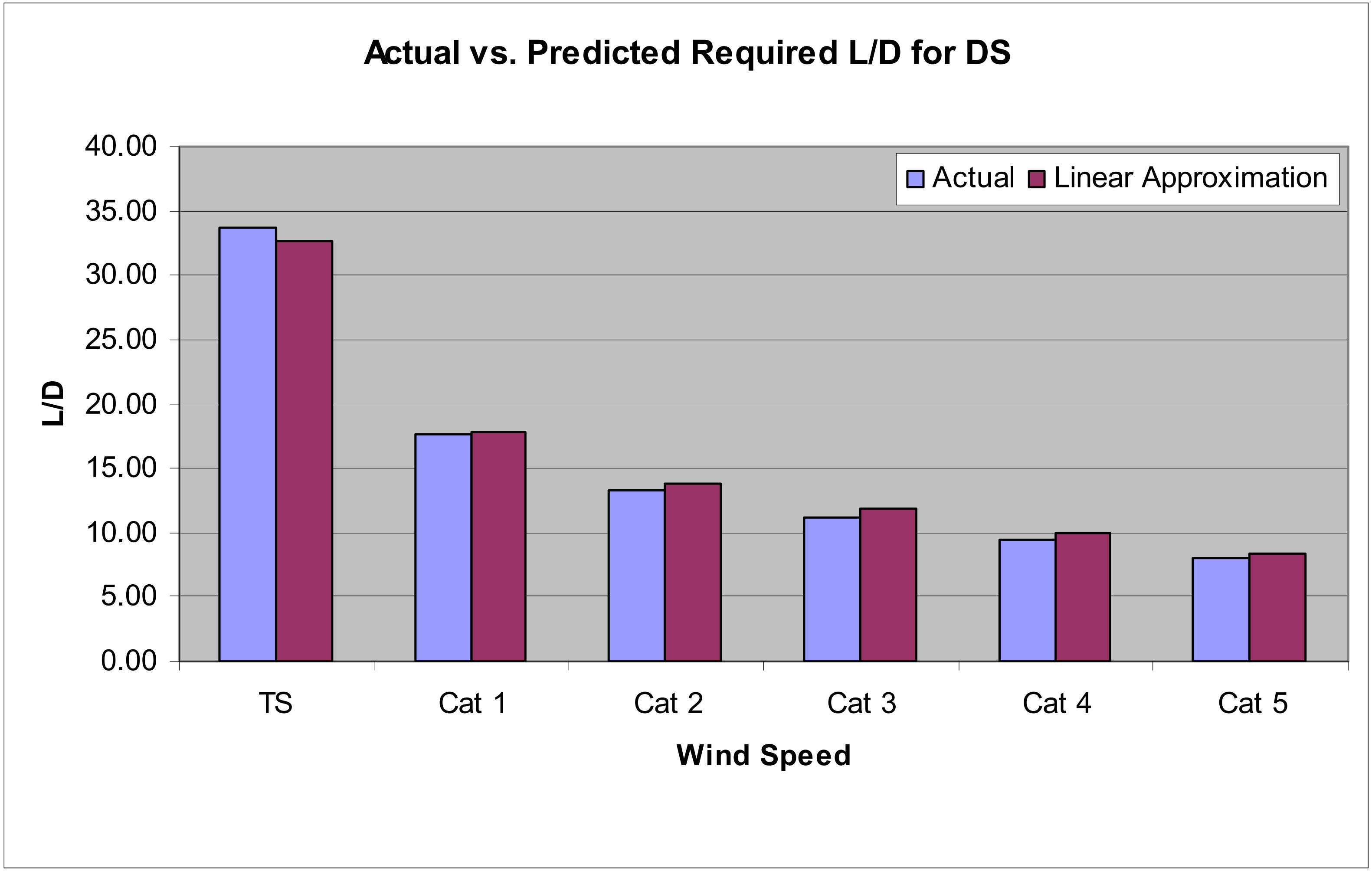


FIG. 4. Radial profiles of windspeed and surface pressure on the north side of Frederic at the 500 m level for the 11 September (11 I) and 12 September (12 H1) flights.

- Small vertical velocity relative to the horizontal velocity (static soaring techniques will not be a reliable means of extracting energy).
- Large horizontal shear at boundary layer (dynamic soaring techniques could be applied)
- Large radial shear (radial dynamic soaring techniques might be applied)
- Turbulence, gust and relationship between wind velocity and wave pattern are unknown.

Required L/D for Hurricane Type



Energy Extraction Analysis

1. Calculate swirl at wingtip

$$Swirl = \frac{C_L}{\pi^2 AR}\frac{b}{R}\sqrt{6\frac{R}{b} - 9\left(\frac{R}{b}\right)^2}$$

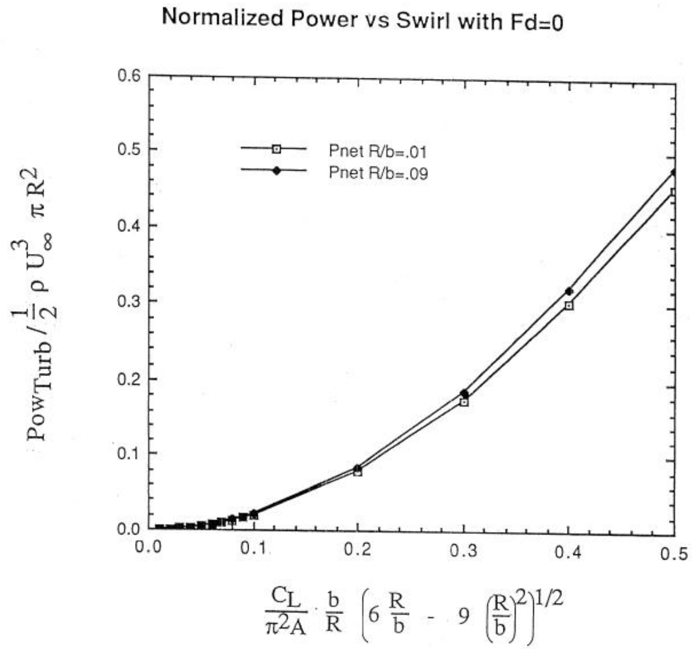
2. Used regression plots (based on full-scale flight data) to find normalized power

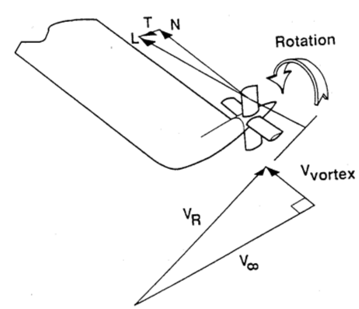
3. Calculate power

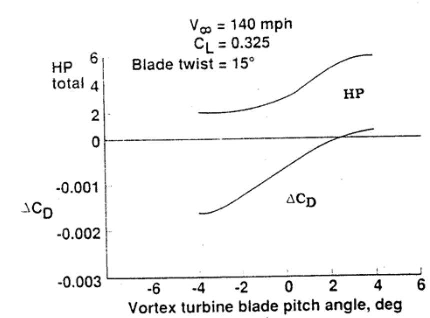
$$P = P_N \frac{1}{2}\rho V_\infty^3 \pi R^2$$

4. If more power is needed, a drag increment is determined

Example: SBXC can extract 1 watt per wing tip at 32 ft/s, 1 lb/ft^2 and C_L=0.7





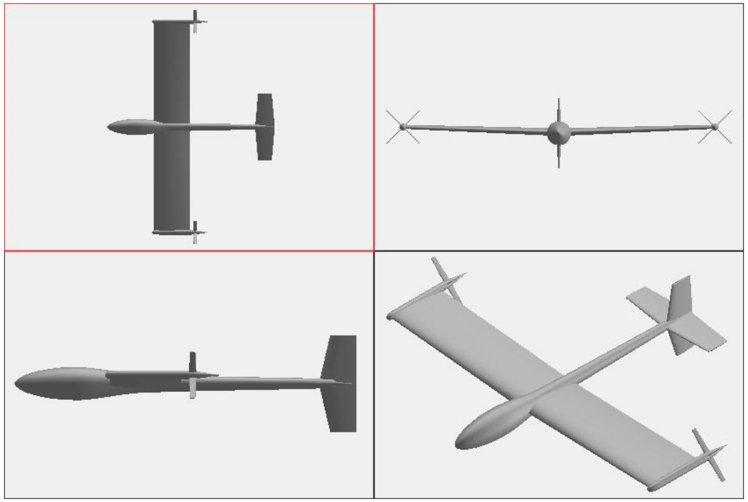


Electronics Power Required

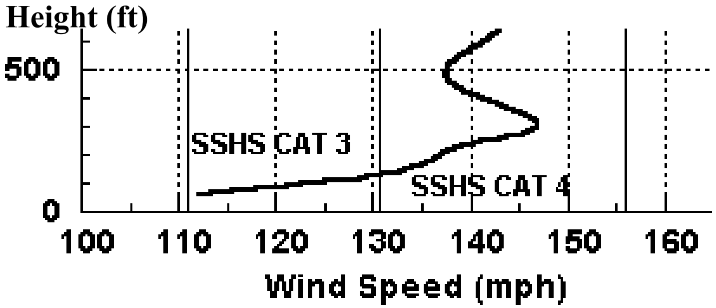
		Weight (oz)	Power (W)
Science Payload			
Temp, Humid, Press		16	0.9
3D Wind & Turbulence		48	24
	Subtotals	64	24.9
Navigation and Control			
Micropilot Autopilot		1	1
Receiver		1.6	0.6
Telemetry		2.6	6
Laser Altimeter		48	15
Servos		12	25
	Subtotals	65.2	47.6
Communications			
Iridium SatCom		48	24
	Subtotals	48	24
	Totals	177.2	96.5
		11.075	lbs

Category III Hurricane Penetrator

- **Wing Span:** 9 ft
- **Wing Area:** 13.56 ft²
- **Aspect Ratio:** 5.97
- **Wing Loading:** 5.3 lbs/ft²
- **Gross Weight:** 72 lbs
  - **Empty Weight:** ~30 lbs
  - **Payload weight:** 11 lbs
  - **Excess weight (batteries):** 31 lbs
- **Airfoil:** HQW 2.5-spec
- **Chord:** 1.5 ft



- **L/D Max:** 12 (@ Re # 2 million)
- **Max maneuver:** 3g
- **Velocity Range:** 85 to 35 kts
- **C_L Range:** .4 to 1.2
- **Tip Turbine Diameter:** 1.38 ft
  - Sized to generate electronic power of 96 W with zero drag penalty
- **Motor Power:** 1 hp per wingtip (sized for climb)
- **Power Required for level flight:** 1.2 kw (1.6 hp)
- **Required Gradient:** 10.7 kts/100ft



Backup Slides

Project Introduction

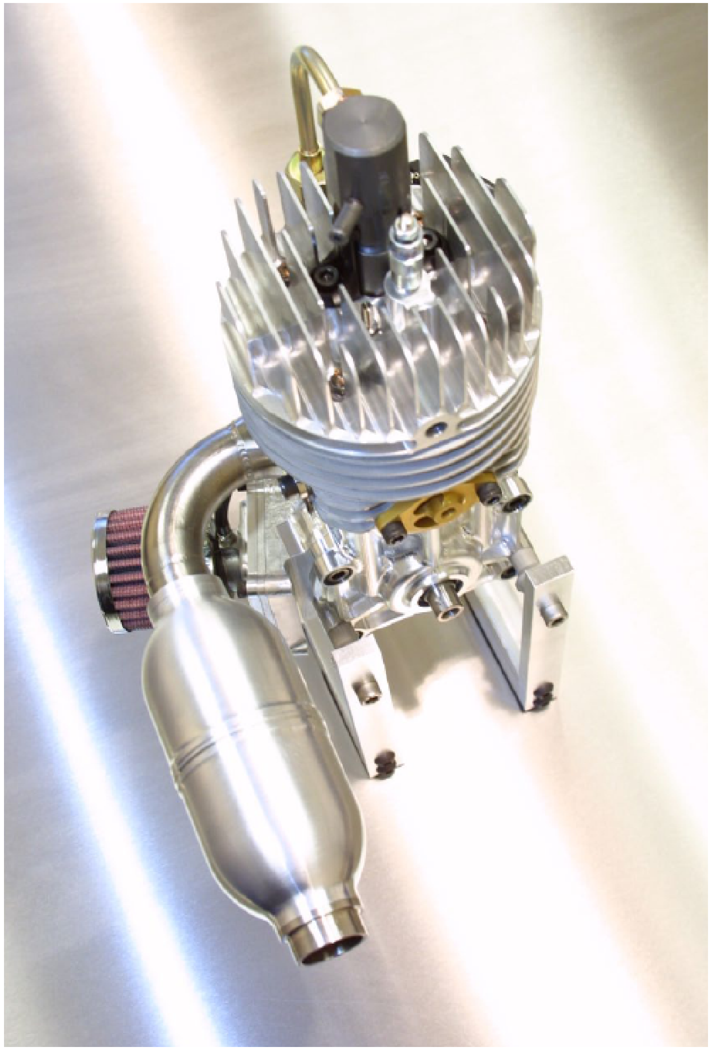
AERONAUTICS

- Reimar is a OGA funded NASA study for the exploration of a long endurance, VTOL UAV capable of a 25 lb payload plus a high data rate SATCOM capability.
- Detailed requirements document provided by OGA, which was reviewed in depth in the Kickoff meeting presentations.
- Since the mission was known to be extremely challenging (due to opposing long endurance and VTOL conflicting requirements), initial guidance indicated desire to explore new concept paths that might be enabled through electric propulsion.
- Study lead determined that this effort was best suited as a collaboration between LaRC and UAV industry partner (with most similar size and type of vehicle – i.e. high aspect ratio wing VTOL with autonomous hover capability). Reasons include
  - Lack of small UAV database and regression-based methodologies.
  - Desire of customer to quickly prototype a concept of interest.
  - Implied importance of autonomous VTOL operations from the requirements.

Project Introduction

- Resources provided of $250K, split between LaRC and MLB, with effort to be completed prior to end of FY 09 calendar year.
  - After LaRC and NIA contract overhead, approximately ~1000 hours available by each partner.
  - Additional Laser task contract for ~$20K for engineering visualizations of 2 concepts to assist OGA with explaining both mission CONOPs and complex vehicle articulations to other customers and funders. These concepts are yet to be selected, with rendering work performed in Oct – Nov.
- Leveraging of this effort is provided by LaRC Redundant Electric VTOL research ($300K study funded by LaRC Chief Scientist to study lead).
  - Development of modified Blade Element Momentum (BEM) Matlab method for use with both rotorcraft and high axial flows (tail sitters) for prop-rotor analysis (Georgia Tech – Sankar/Bain).
  - Development of wake velocity model from BEM data and slipstream control surface force model for vehicle control analysis (MIT – How).
- MLB and LaRC tools were not standardized, to permit cross comparison of methodologies, with initial validation to an existing baseline with sufficient data.

Cosworth AE1 Diesel Engine



A detailed dataset of their new (larger) engine is pending, as that information has not been released to the public. This should include dyno runs with power and sfc, with more detailed weights.

Until then, the sfc and power to weight were scaled from the current (smaller) engine.

Cosworth AE1 Diesel Engine

Assumptions

Engine

- 0.55 lbs/(hp*hr)
- 2.39 lbs/hp

Battery

- 350 watt*hrs/kg

Generator & Motor

- 0.5 lbs/hp
- 90% Conversion Efficiency

Hover Power Required	14.5	Hp
Hover Power Time	20	Min
Cruise Power Required	4.3	Hp
Cruise Power Time	23.67	Hrs
Engine Size	5.33	Hp

Engine Weight	12.7	Lbs
Generator Weight	2.7	Lbs
Motor Weight	8.1	Lbs
Battery Weight	17.7	Lbs
Fuel Weight	70.4	Lbs
Total	111.5	Lbs

Study Assumptions

General

- Science Payload
  - Weight = 25 lbs
  - Power = 400 W (only during loiter)
  - Volume = 2500 cubic inches
- SatComm Payload (based on the ViaSat VMT-1220LA)
  - Weight = 35 lbs
  - Power = 275 watts
  - Volume = 3760 cubic inches
    - Modem : 8”x5”x14” (Estimate)
    - Antenna: 12”x18”x14”
    - ACU: 8”x11”x2”
- Autopilot, Servos, Power Conditioning
  - Weight = 5 lbs
- Wing Aspect Ratio is limited to 15
- Tazenflugel and Dos Samara Structural mass fraction = 40%
- V-Bat Structural mass fraction = 30%
- V-Bat duct diameter to 25% of wing span,
- V-Bat fan hub radius of 0.5 ft.
- No recharging of hybrid concepts

Mission

- Vertical Climb to 200 feet at 200 ft/min
  - MLB is using a 25% thrust margin (T/W=1.25)
- Horizontal climb at constant CL (for best L/D) from 200 ft to 18,000 ft
  - NASA is using the CL for best L/D for that wing geometry
    - Note: I understand that best CL for a prop is at minimum power not at minimum drag, but I am using CL at best L/D to prevent another nested convergence loop in the analysis. The sensitivity of this to MTOW is minor and this assumption is slightly conservative.
    - Rate of climb is equal to 500 ft/min. Power required falls out.
  - MLB is using a CL of 0.8
- Cruise 217.5 miles at 100 kts
  - Distance covered in climb is included in 217.5 miles
- Loiter at constant CL for 20 hrs
  - NASA is using CL at best L/D
  - MLB is using a loiter at 50 kts to assure adequate margin above stall
- Cruise 217.5 miles at 100 kts
- Descend at 500 ft/min to 500 ft at 100 kts
  - Distance covered in descent is included in 217.5 miles
- Loiter at constant CL (for best L/D) for 5 minutes
- Vertical Descent from 500 ft to 0 ft at -50 ft/min

Alternate Mission

- Replace Loiter segment with a sensor placement at a 15,000 ft altitude.
  - Note: There is no requirement for the vehicle to land, but it must be capable of pushing a sensor into the ground within 1.5 meters of the intend location.

Propulsion

- Cosworth AE1 Diesel Engine
  - BSFC = 0.55 lbs/(hp*hr)
  - BSFC is constant with throttle setting
    - For Diesel engines this is an appropriate assumption. Note that the Cosworth AE1 has a BSFC of 0.48 lbs/(hp*hr) at 50% power
    - For Gas engines this is a poor assumption because of the throttle losses at part power.
  - Power to Weight = 2.39 lbs/hp
    - MLB will use 1.5 lbs/hp for V-Bat (based upon larger engine size required achieving higher hp/lb)
- Turbo Charging
  - Reduce Power to Weight (i.e. make engine heavier) by 0.25 lbs/hp
  - Can hold sea level power to 10,000 ft then follow standard atmosphere air density lapse rate.
  - Loosely derived based on Rotax 4 stroke engines.
- Electric Motors and Generators
  - Power to Weight = 0.5 lbs/hp_electric
  - Conversion Efficiency = 90%
- Batteries
  - 350 watt*hrs/kg (current best available)
- Horizontal Flight Propeller Efficiency
  - 85%

Rotor Efficiency

- NASA Actuator Disk Momentum Method
  - tip_loss_factor = .97;
  - induced_power_factor = 1.13;
  - tip_speed = 400;
  - CD = .01;
  - rotor_area = pi*radius^2;
  - sigma = radius*ave_cord/rotor_area;
  - tot_power = induced_power + profile_power + climb_power;

$$Power_{Induced} = \frac{InducedPowerFactor * Weight^{1.5}}{TipLossFactor * \sqrt{2 * RotorArea * rho}}$$

$$Power_{Profile} = \frac{1}{8} * rho * RotorArea * TipSpeed^{3} * Sigma * C_{D}$$

$$Power_{Climb} = \mathrm{RateOfClimb} * Weight$$

  - For Dos Samara account for down load on inboard wing.

$$DownLoad = \mathrm{DiskLoading} * BlockageArea$$

    - Also assumed that inboard wing had a 40% cord flap that deflected down to reduce blockage area.
- MLB Blade Element Method

Dos Samara Wetted Area Build Up → CD_O

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Skin Friction

Component	Wetted Area	Mean Chord	Avg Re#	% Lam	% Turb	T/C	Length/Diam	CDo Component
H Tail	6.3	0.85	474,942	50%	50%	15%		0.0014
V Tail	2.3	0.75	419,067	50%	50%	15%		0.0005
Inboard Wing	39.1	1.7	949,885	50%	50%	17%		0.0075
Fuse	23.7	7	3,911,291	15%	85%		4.67	0.0043
Wing	17.9	1.11	620,219	50%	50%	15%		0.0037
Pod	2.4	2	1,117,512	25%	75%		6.67	0.0004
Batteries	15.3	1.6	894,009	50%	50%	20%		0.0032
Totals	107.0							0.0209

Separated Flow

Component	Base Area	CDo Component
	0	0
Totals	0	0

- Skin Friction + Separated Flow C_{Do} = 0.0209
- XFLR5 C_{Do} = 0.0093
  - Parasite C_{Do} = 0.0116
- Cooling Drag C_{Do} = 0.0019 (10%)
- Total C_{Do} = 0.023

Surrogate Analytic Model

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- Allows wing aspect ratio and area to be varied without the need to build another aerodynamic model.
- Fuselage and other miscellaneous drag (C_{Do2}) should not change as wing area is varied.

$$C_{Do} = C_{Do1} + C_{Do2} * \frac{S_{Baseline}}{S} \qquad C_D = C_{Do} + \frac{C_L^2}{\pi * AR * e} + k * C_L$$

Tazenflugel

- C_{Do1} = 0.0134
- C_{Do2} = 0.0076
- e = 0.51
- k = -0.019
- $S_{Baseline}$ = 27.46

Dos Samara

- C_{Do1} = 0.0134
- C_{Do2} = 0.0116
- e = 0.51
- k = -0.019
- $S_{Baseline}$ = 27.46

Dos Samara Weights

	Max Takeoff Weight =	258.00 lbs		
	Payload =	60.00 lbs	23.26%	Gross
	Avionics =	5.00 lbs	1.94%	Gross
	Fuel Consumed =	54.94 lbs	21.30%	Gross
	Battery Weight =	6.28 lbs	2.43%	Gross
7.0 HP	Engine Weight =	18.48 lbs	7.16%	Gross
7.0 HP	Generator Weight =	3.49 lbs	1.35%	Gross
12.9 HP	Electric Motor(s) Weight =	6.43 lbs	2.49%	Gross
	Other System Weight =	0.00 lbs	0.00%	Gross
	Remaining Weight for Airframe =	103.38 lbs	40.07%	Gross

Dos Samara Mission Outputs

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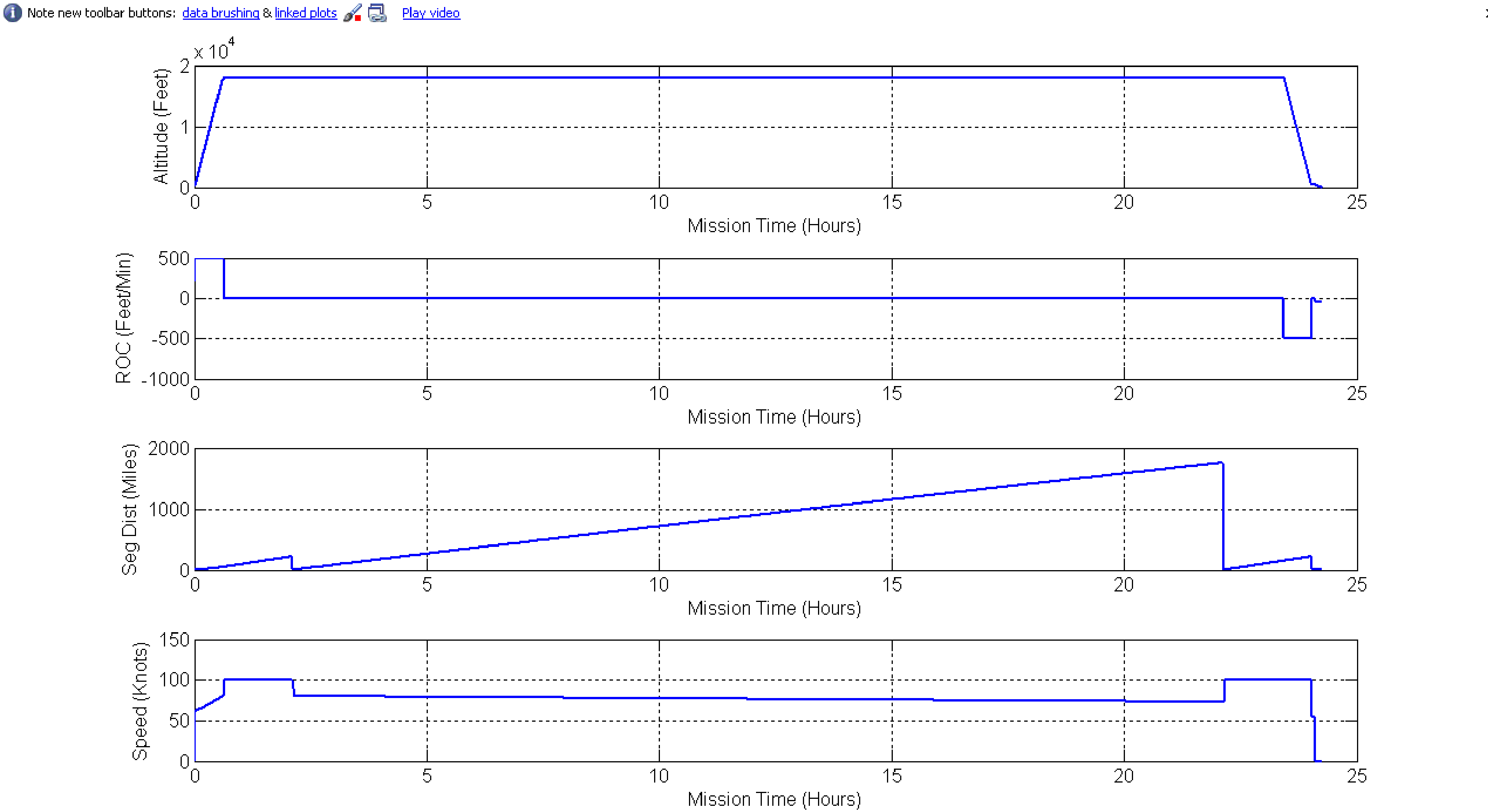

Dos Samara Mission Outputs

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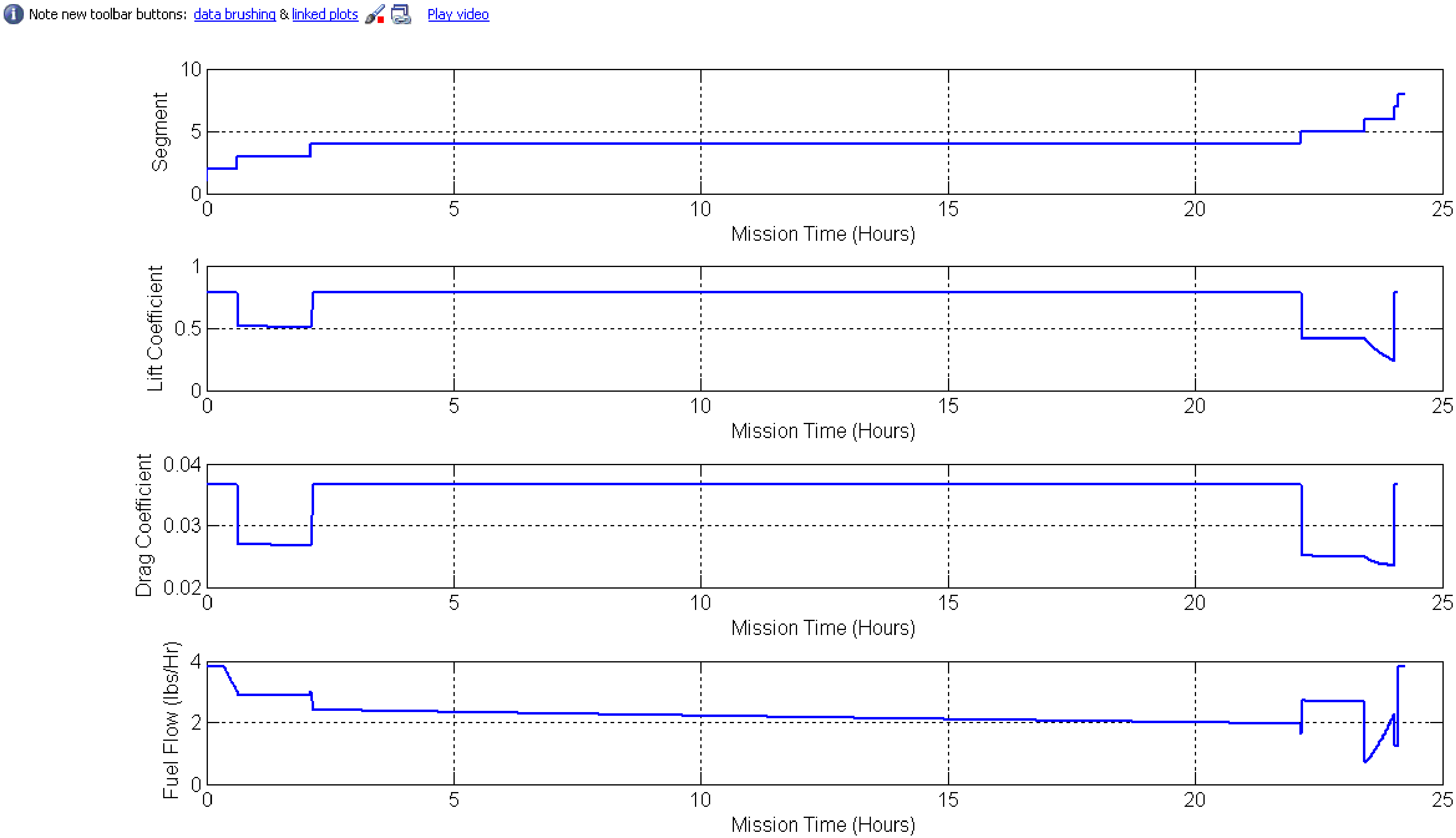
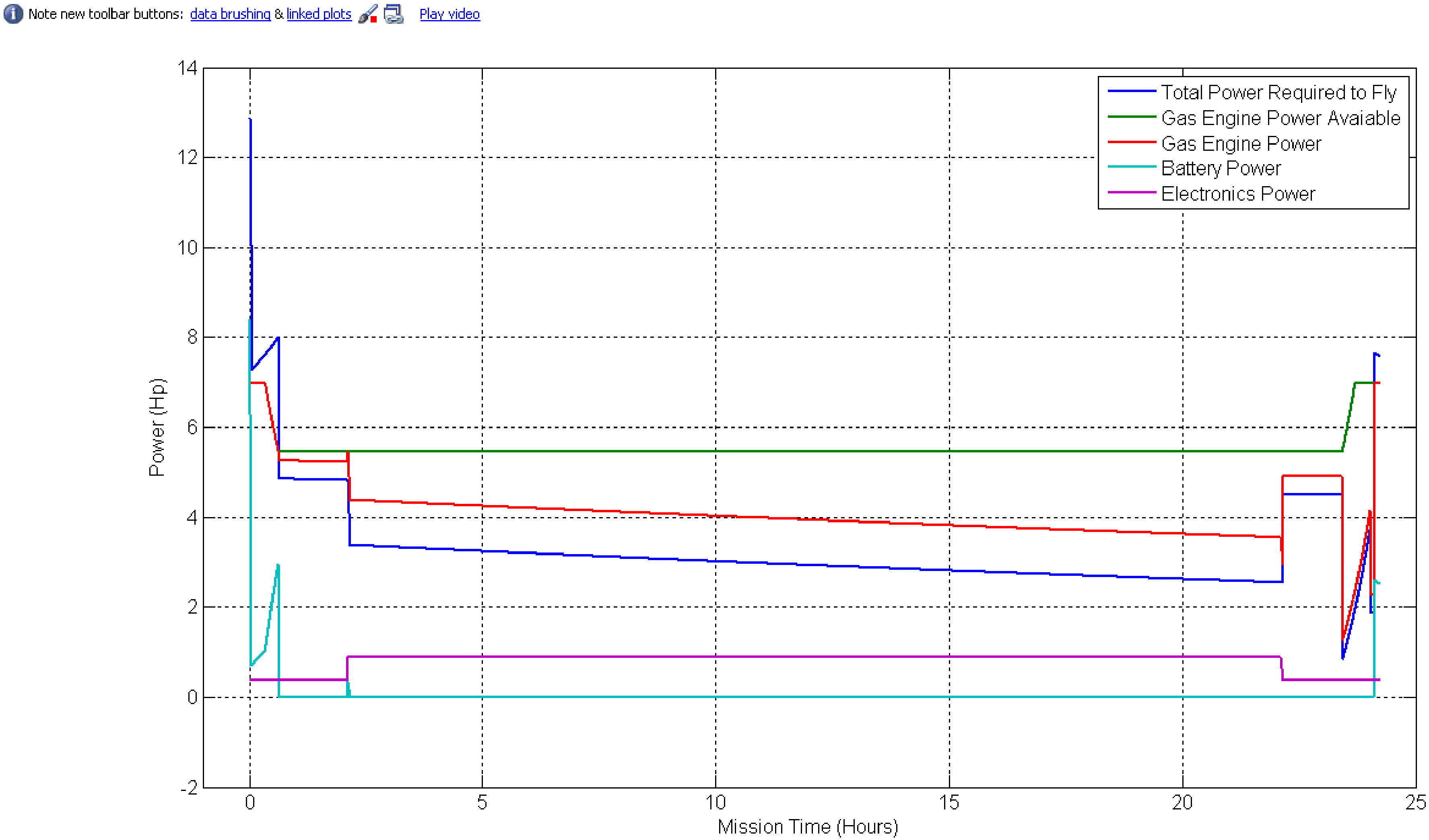


Dos Samara Mission Outputs

AERONAUTICS



Rotor Blade Element Analysis

Sea Level

Weight	258 lbs
Vertical Climb Speed	200 ft/min
Tip Speed	300 ft/sec
Induced Power	11.7 Hp
Profile Power	1.7 Hp
Total Rotors Power	13.4 Hp
Actuator Disk Method	13.1 Hp

15,000 ft

Weight	251 lbs
Vertical Climb Speed	100 ft/min
Tip Speed	325 ft/sec
Induced Power	12.6 Hp
Profile Power	1.4 Hp
Total Rotor Power	14.0 Hp
Actuator Disk Method	N/A

Notes:

- Offline Post Analysis
- Power quoted is for both rotors.
- 253 lbs is the weight at the end of the first 100 knot dash.

Requirements Sensitivities

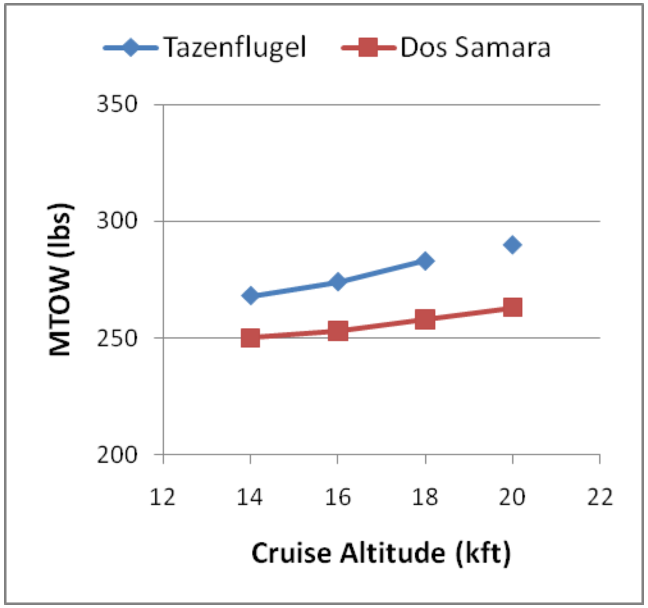
- Dash Speed – 110, 100, 90, 80 kts
- Cruise Altitude – 20, 18, 16, 14 Thousands of Feet
- Vertical Flight Rate of Climb – 200, 100, 50 ft/min
- Deice System Weight – 2, 1, 0 % MTOW

Nominal Value

Note: will not present sensitivity to span constraint because analysis does not have the fidelity to do so.

Cruise Altitude

Cruise Altitude (kft)	Tazenflugel MTOW (lbs)	Dos Samara MTOW (lbs)
20	*290*	263
18	283	258
16	274	253
14	268	250



Notes:

- Tazenflugel 20 k ft did not converge and correlates to 39.2% Airframe Weight

Vertical Flight Rate of Climb

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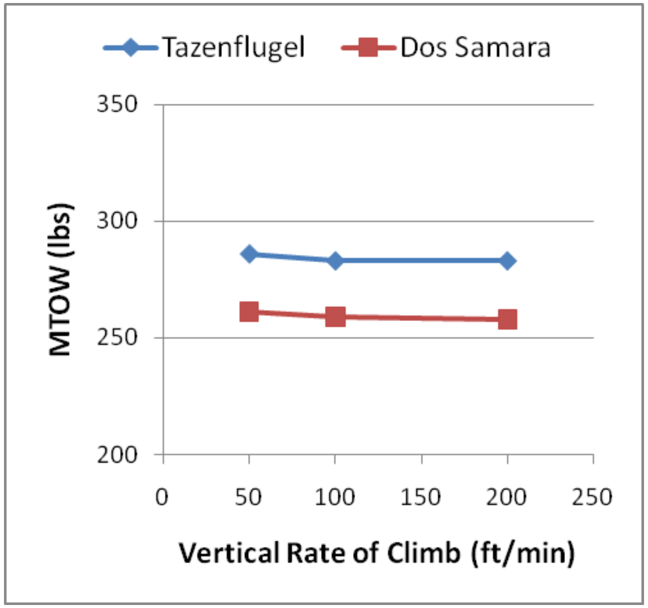
Rate of Climb (ft/min)	Tazenflugel MTOW (lbs)	Dos Samara MTOW (lbs)
200	283	258
100	283	259
50	286	261



Notes:

- This is rate of climb is referring to VTOL phase only.
- Horizontal flight rate of climb is 500 ft/min for all listed data.

Vertical Flight Rate of Climb

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Dos Samara

200 ft/min

	Max Takeoff Weight =	258.00 lbs	
	Payload =	60.00 lbs	23.26% Gross
	Avionics =	5.00 lbs	1.94% Gross
	Fuel Consumed =	54.94 lbs	21.30% Gross
	Battery Weight =	6.28 lbs	2.43% Gross
7.0 HP	Engine Weight =	18.48 lbs	7.16% Gross
7.0 HP	Generator Weight =	3.49 lbs	1.35% Gross
12.9 HP	Electric Motor(s) Weight =	6.43 lbs	2.49% Gross
	Remaining Weight for Airframe =	103.38 lbs	40.07% Gross

100 ft/min

	Max Takeoff Weight =	259.00 lbs	
	Payload =	60.00 lbs	23.17% Gross
	Avionics =	5.00 lbs	1.93% Gross
	Fuel Consumed =	55.12 lbs	21.28% Gross
	Battery Weight =	6.90 lbs	2.66% Gross
7.0 HP	Engine Weight =	18.55 lbs	7.16% Gross
7.0 HP	Generator Weight =	3.50 lbs	1.35% Gross
12.1 HP	Electric Motor(s) Weight =	6.06 lbs	2.34% Gross
	Remaining Weight for Airframe =	103.88 lbs	40.11% Gross

50 ft/min

	Max Takeoff Weight =	261.00 lbs	
	Payload =	60.00 lbs	22.99% Gross
	Avionics =	5.00 lbs	1.92% Gross
	Fuel Consumed =	55.41 lbs	21.23% Gross
	Battery Weight =	7.77 lbs	2.98% Gross
7.1 HP	Engine Weight =	18.69 lbs	7.16% Gross
7.1 HP	Generator Weight =	3.53 lbs	1.35% Gross
11.8 HP	Electric Motor(s) Weight =	5.91 lbs	2.27% Gross
	Remaining Weight for Airframe =	104.68 lbs	40.11% Gross

Deice System Weight

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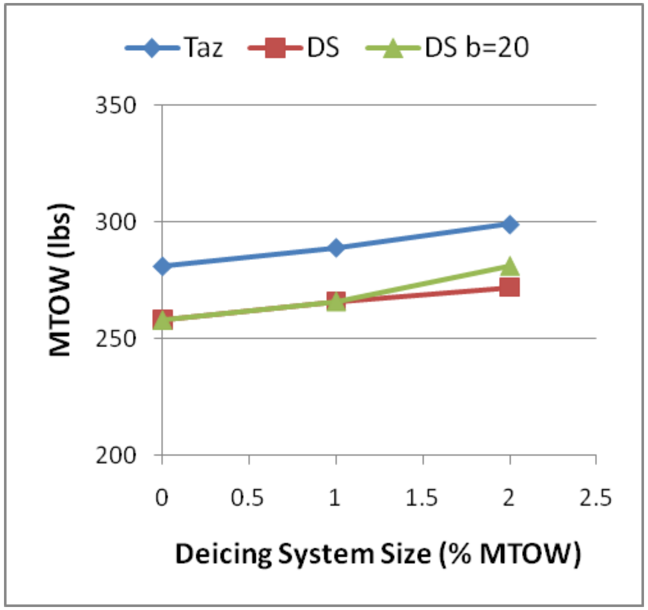
System Weight (%MTOW)	Tazenflugel MTOW (lbs)	Dos Samara MTOW (lbs)	Span Constraint Dos Samara MTOW (lbs)
2	299	272	281
1	289	266	266
0	281	258	258

System Weight (%MTOW)	Tazenflugel Span (ft)	Dos Samara Span (ft)	Span Constraint Dos Samara Span (ft)
2	20.67	20.20	20.00
1	20.32	19.97	19.97
0	20.10	19.67	19.67



Notes:

- First 2 columns no span constraint
- No effect on aerodynamic model
    - For example, no additional drag from deicing boots.
- This data may be used to assess any aircraft system that is a function of MTOW

Sizing Sensitivities

- Wing Loading with Combustion Engine Power Loading
  - Tazenflugel
    - Wing Loading – 10, 10.5, 11 lbs/ft^2
    - Power Loading – 30, 34, 38, 40 lbs/hp
  - Dos Samara
    - Wing Loading – 9, 10, 11 lbs/ft^2
    - Power Loading – 31, 34, 37, 40 lbs/hp
- Airframe Weight - 0.35, 0.4, 0.45 % MTOW
- No Electric Dos Samara

Nominal Value

Tazenflugel

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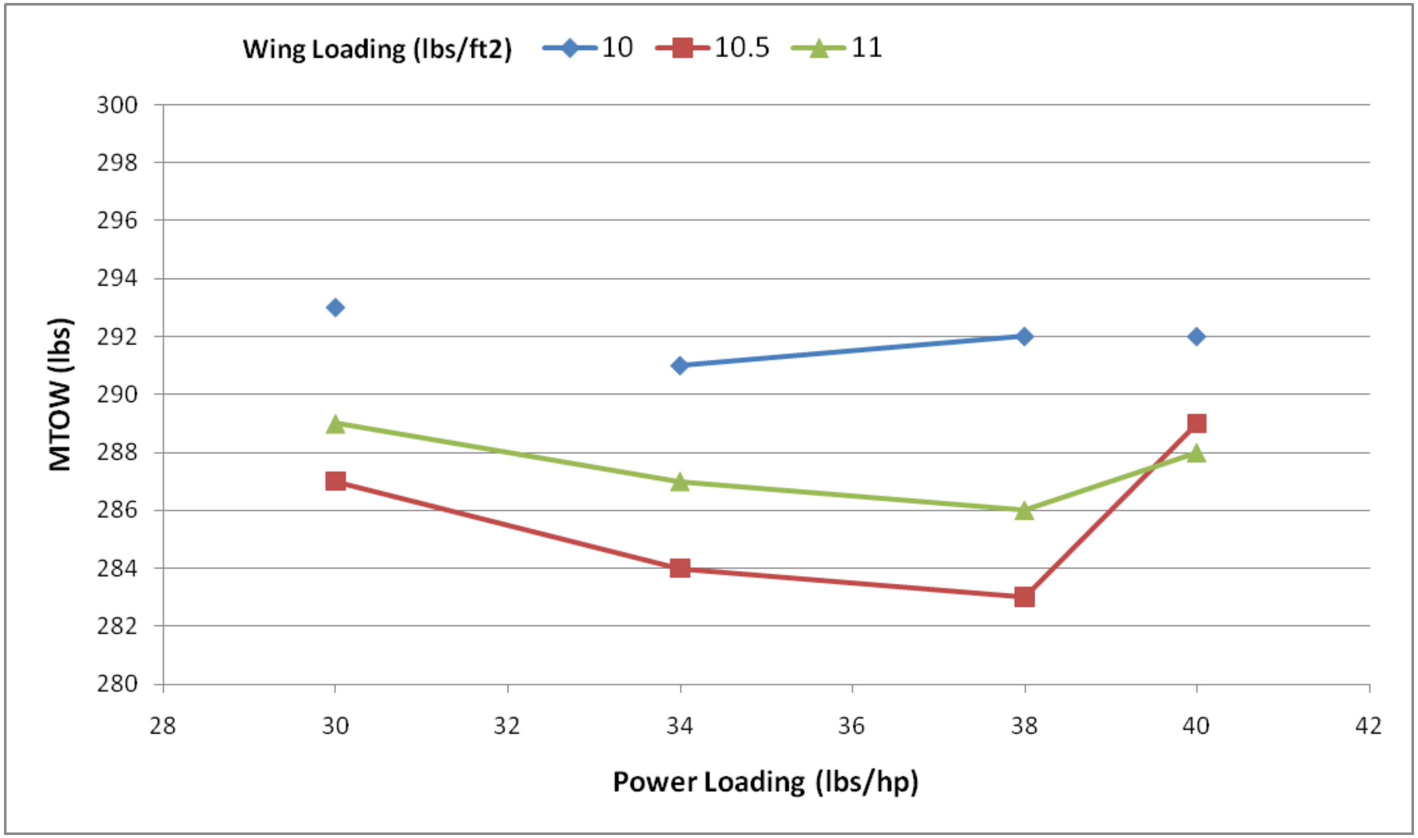


Tazenflugel

Wing Loading (lbs/ft^2)

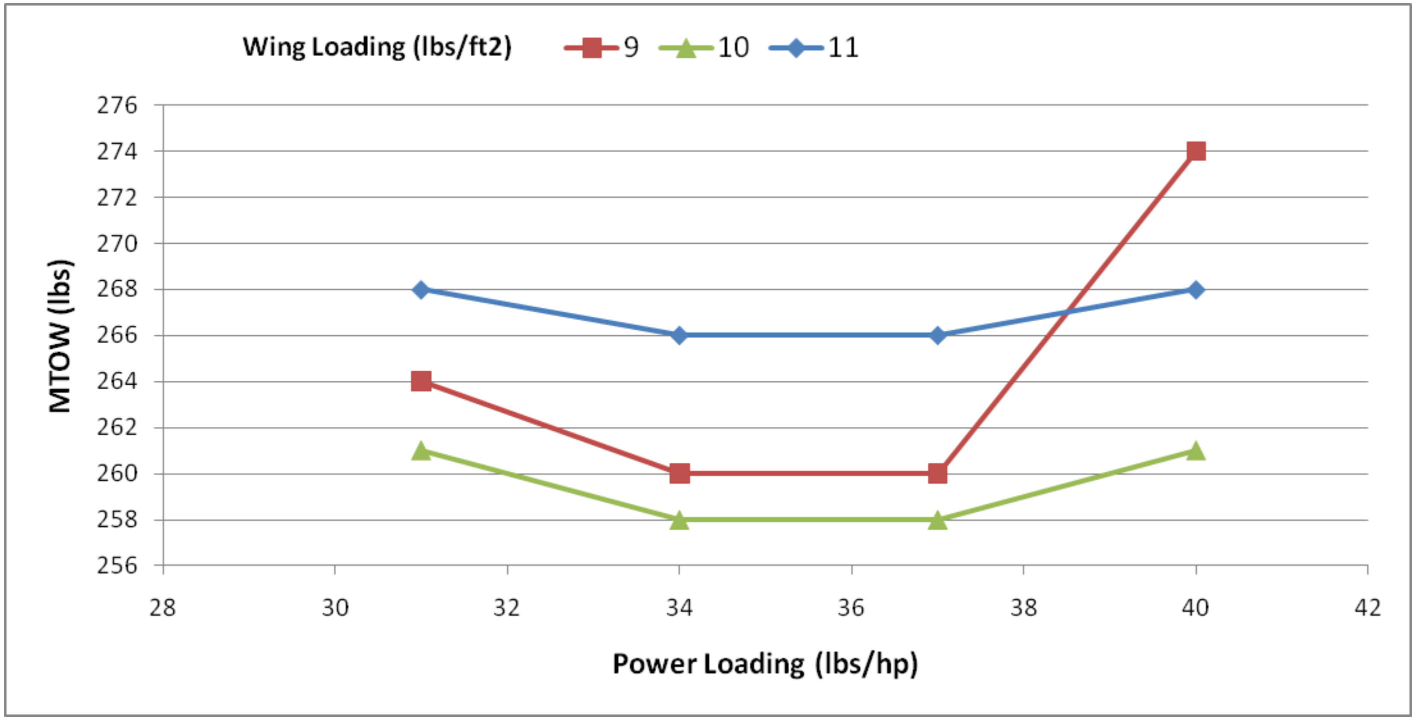
Combustion Engine Power Loading (lbs/hp)

	10	10.5	11
30	*293*	287	289
34	291	284	287
38	292	283	286
40	*292*	289	288

Notes:

- Power loading of 30 and 40 at a wing loading of 10 did not converge.
- Listed MTOW is at weight with highest airframe weight percent
  - 30 lbs/hp = 39.9% Airframe Weight
  - 40 lbs/hp = 39.5% Airframe Weight

Dos Samara


Wing Loading (lbs/ft2)
9
10
11
276
274
272
270
268
266
264
262
260
258
256
MTOW (lbs)
28
30
32
34
36
38
40
42
Power Loading (lbs/hp)

Dos Samara

Wing Loading (lbs/ft^2)

Combustion Engine Power Loading (lbs/hp)

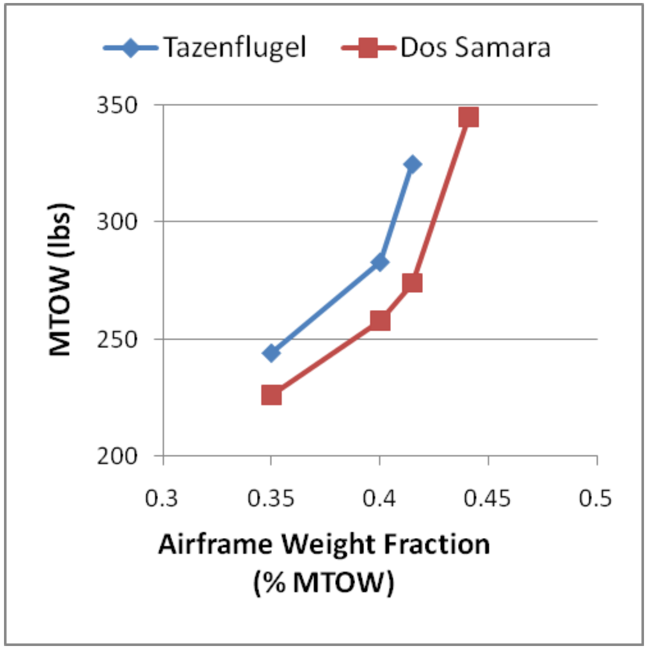
	9	10	11
31	264	261	268
36	260	258	266
37	260	258	266
40	274	261	268

Airframe Weight

Airframe Weight (%MTOW)	Tazenflugel MTOW (lbs)	Dos Samara MTOW (lbs)
44.1		345
41.5	325	274
40	283	258
35	244	226

Notes:

- Reference Tazenflugel max feasible airframe weight
  - 41.5% MTOW
- Reference Dos Samara max feasible airframe weight
  - 44.1% MTOW



No Electric Dos Samara

MTOW (lbs)

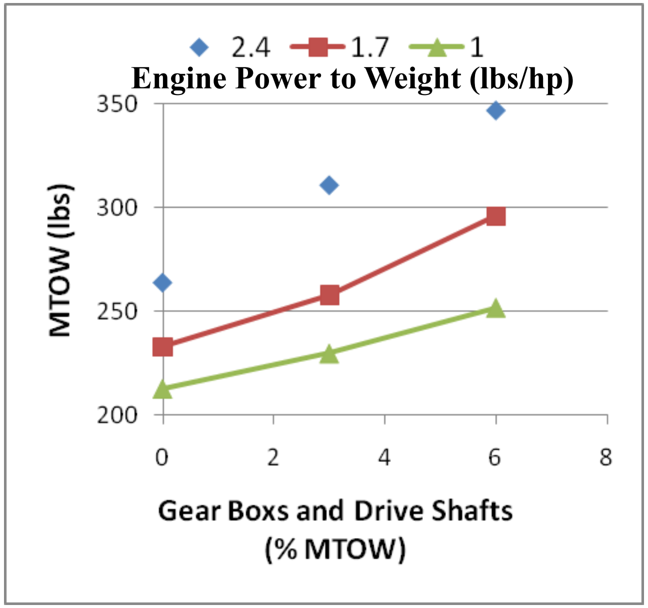
	2.4	1.7	1
6	*347*	*296*	252
3	*311*	258	230
0	264	233	213

Airframe Weight (%MTOW)

	2.4	1.7	1
6	*36.7*	*39.48*	40
3	*39.06*	40	40
0	40	40	40

Notes:

- Reference Dos Samara MTOW = 258 lbs
- 98% efficient rotor gear boxes
- 0.25 lbs/hp turbocharger still included
  - For example, 2.4 + 0.25 = 2.65 lbs/hp is rubber engine weight



No Electric Dos Samara

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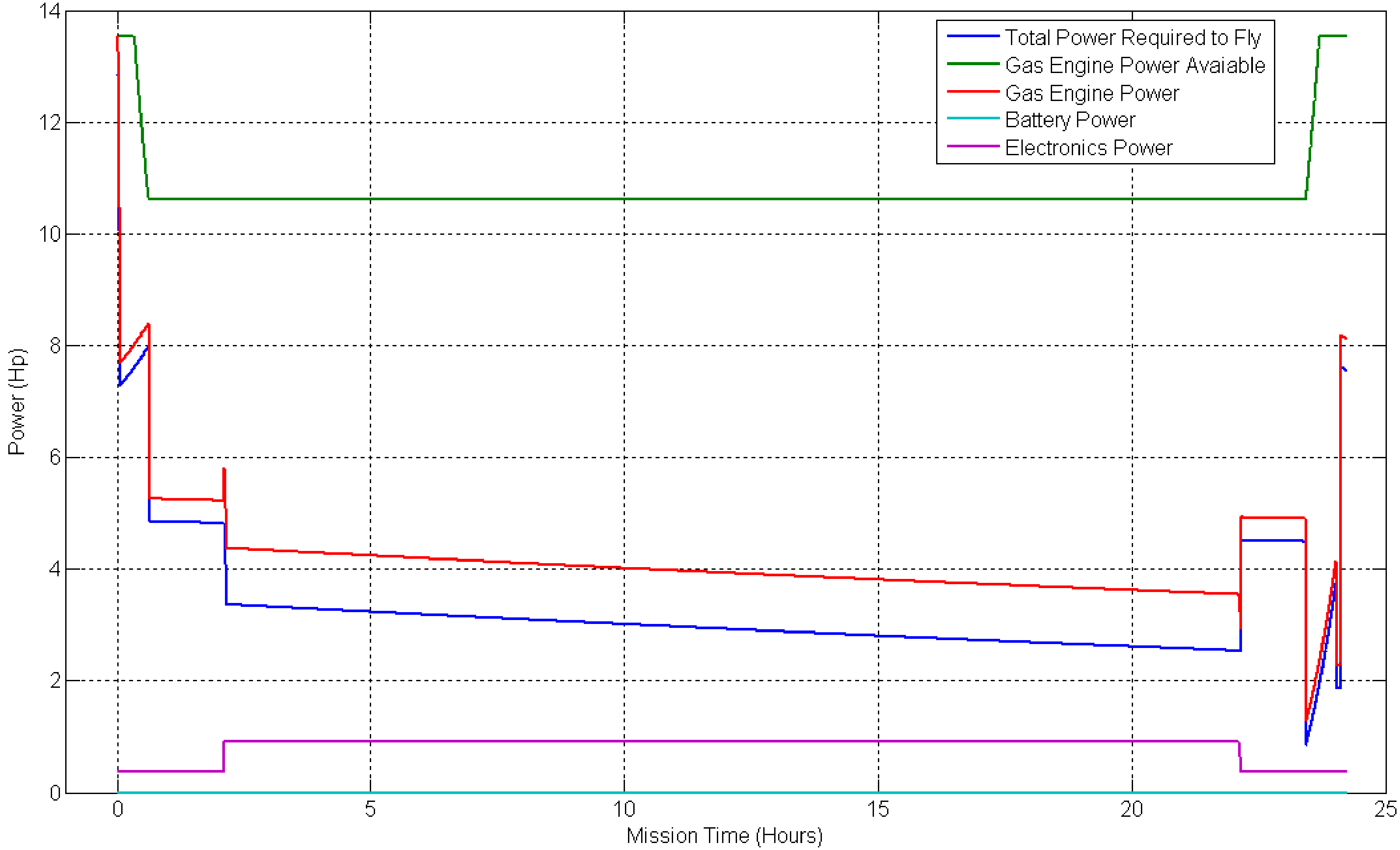
Engine Power to Weight = 1.7 lbs/hp   Gear Boxes and Drive Shafts = 3% MTOW

Note new toolbar buttons: data brushing & linked plots   Play video



Technology Level Sensitivities

- SatComm Weight – 35, 25, 15 lbs
- Combustion Motor Weights – 2.4,1.7, 1.0 lbs/hp
- BSFC - .55, .45, .35 lbs/(hp*hr)
- Electric Motor/Generator Weights – 2, 4, 6 hp/lb
- Electric Motor/Generator Conversion Efficiencies – 90, 93, 96 %
- Battery Energy Density – 350, 450, 550 watt*hrs/kg

Nominal Value

SatComm Weight

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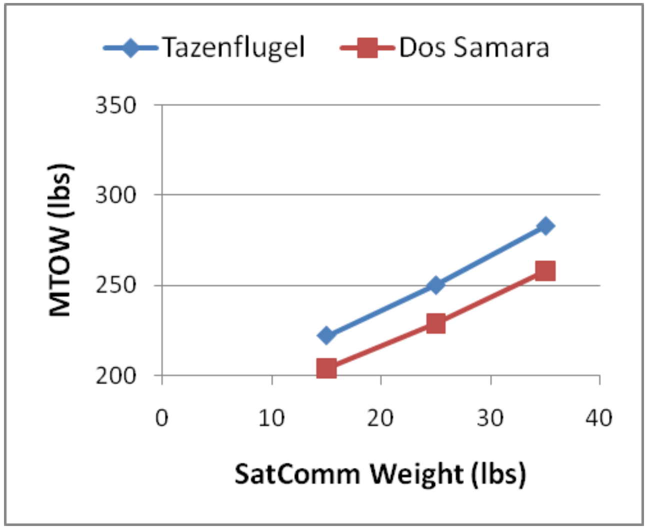
SatComm Weight (lbs)	Tazenflugel MTOW (lbs)	Dos Samara MTOW (lbs)
35	283	258
25	250	229
15	222	204

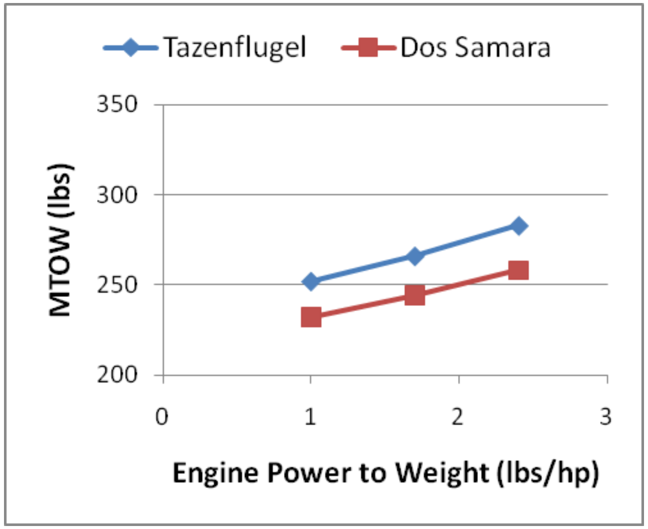


Notes:

- SatComm volume and power is unchanged.
  - Power = 275 watts
  - Volume = 3760 cubic inches
    - Modem : 8”x5”x14” (estimate)
    - Antenna: 12”x18”x14”
    - ACU: 8”x11”x2”

Combustion Motor Weights

Engine Power to Weight (lbs/hp)	Tazenflugel MTOW (lbs)	Dos Samara MTOW (lbs)
2.4	283	258
1.7	266	244
1.0	252	232

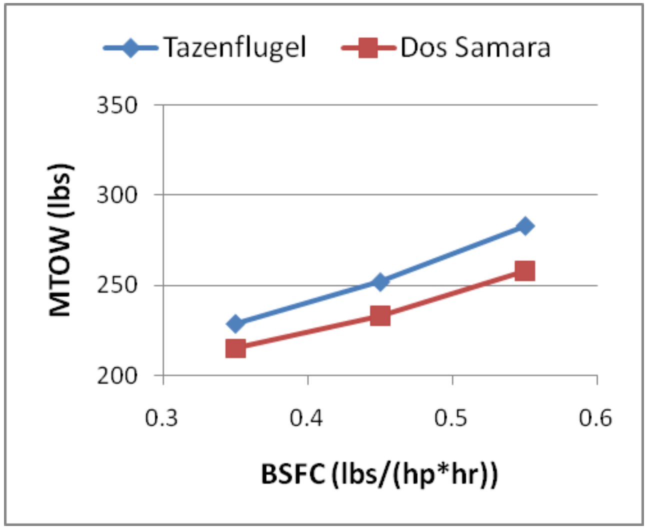


Notes:

- These MTOWs still include the weight of the turbocharger (.25 lbs/hp)

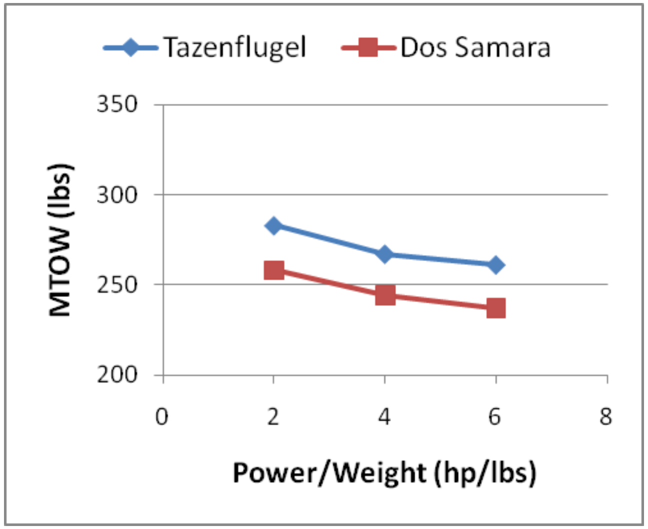
BSFC

BSFC (lbs/(hp*hp))	Tazenflugel MTOW (lbs)	Dos Samara MTOW (lbs)
0.55	283	258
0.45	252	233
0.35	229	215



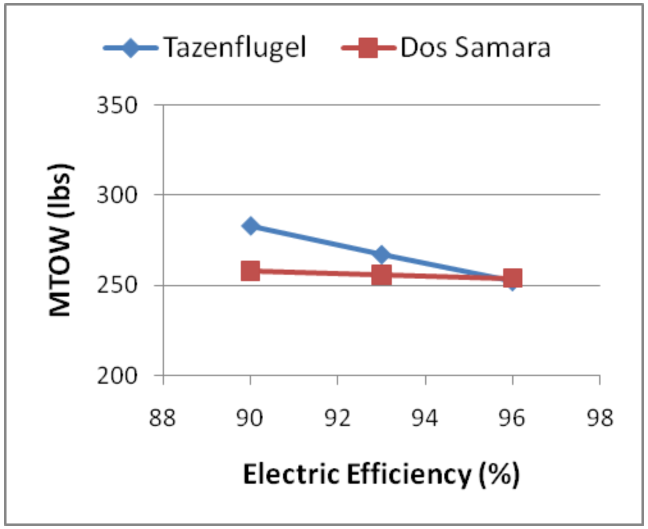
Electric Motor/Generator Weights

Pow/Wgt (hp/lbs)	Tazenflugel MTOW (lbs)	Dos Samara MTOW (lbs)
2.0	283	258
4.0	267	244
6.0	261	237



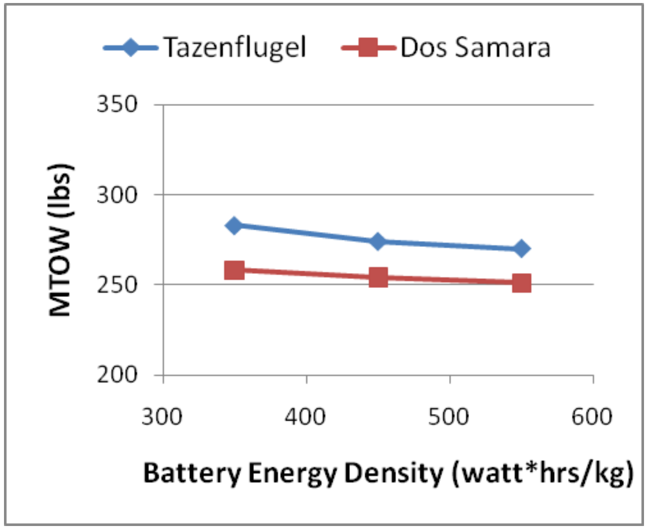
Electric Motor/Generator Conversion Efficiencies

Efficiency (%)	Tazenflugel MTOW (lbs)	Dos Samara MTOW (lbs)
90	283	258
93	267	256
96	252	254



Battery Energy Density

Battery (w*hrs/kg)	Tazenflugel MTOW (lbs)	Dos Samara MTOW (lbs)
350	283	258
450	274	254
550	270	251



Notes:

- These vehicles have not been reoptimized.
  - Expect minor improvements in MTOW
  - Expect smaller combustion engines

Currently In Production Batteries

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Company	Type	WHr/kg	WHr/l	W/kg	Cycles	$/50kWHr
	Lead Acid	40	65	350	400	4500
	NiMH	86	170	70	1500	90000
Valence	Lithium Ion	90	140	100	2000	57150
Zebra	NaNiCl2	90	100	150	3000	60000
Xellerion	Ni-Zn	60	120	875	500	
Toshiba SCiB	Lithium Ion	78	131	10000	5000	
Altair Nano	Lithium Ion	90		7000	20000	120000
Advanced Battery	Lithium Polymer		191		2000	
ThunderSky	LiFePO4	94	136		2000	
PHET PE-1150	LiFePO4	93	213	300	2000	39000
PHET	LiFePO4 Poly	125	240		500	
Huanya	LiFePO4	100	153			
Valence Epoch	LiFePO4	84	120	158	2000	
A123 Systems	LiFePO4	108	230	2400	3000	50000
Delaware Power Systems	Lithium Ion	130	235	675	500	
Fly Power	Lithium Polymer	133	270	2000		
Saft Batteries	L-Ion (VLM)	136	285	800	500	
Panasonic CGR18650AF	Li-Ion (2.0 Ah)	174	417	200	500	25000
Panasonic CGR18650CF	Li-Ion (2.2 Ah)	184	457	200	500	
Panasonic CGR18650E	Li-Ion (2.5 Ah)	203	533	200	500	
Panasonic 18650	Li-Ion (2.9 Ah)	230	600		500	
Ever Spring	Lithium Fluoride	102	330	720	1000	35400
Electrovaya	Lithium Polymer	225	470			
Electrovaya	Lithium Polymer	330	650			
Sion Power	Lithium Sulfur	350	350	400		

http://www.plasticlabels.ca/index_files/compareEVbatteries.htm

Technology Priority Ranking

Tazenflugel

1. SatComm Weight
2. BSFC
3. Engine P/W
4. Electric Motor Efficiency
5. Electric Motor P/W
6. Battery Energy Density

Dos Samara

1. SatComm Weight
2. BSFC
3. Engine P/W
4. Electric Motor P/W
5. Battery Energy Density
6. Electric Motor Efficiency

Rankings based on sensitivity results and qualitative assessment

- All-on technology Dos Samara yields a MTOW of 146 lbs, with a 14.8 ft span, wing area of 14.6 ft^2, 3.9 hp recip engine, 2.8 hp elec motor (each), with a L/Dmax = 17.4 (fuselage drag dominates).
- All-on technology Tazenflugel yields a 142 MTOW of lbs.

Conclusions

- The concepts always pushed towards the largest wing area possible, that maintained an aspect ratio of 15 (constraint limit), within the 20 span (constraint limit).
- Tazenflugel concept is on the edge of the feasible design space (slight penalties cause convergence infeasibility).
- Dos Samara is a more robust concept to assumption uncertainties.
  - Primarily a result of direct connection of engine to pusher prop (no conversion losses) Dos Samara results in a smaller vehicle.
  - Since it is a smaller vehicle, it is not pushed as far into the corner of the design space (i.e. the vehicle can converge easier).
- Increasing the span constraint of 20 ft even slightly will assist in reducing both concept development risks.
- Risk reduction efforts should be undertaken for the structural weight and conversion dynamics and control assumptions, prior to full scale development commitment.
- Study results indicate that the requirements are potentially within reach of a near-term effort that embraces unconventional concept development.