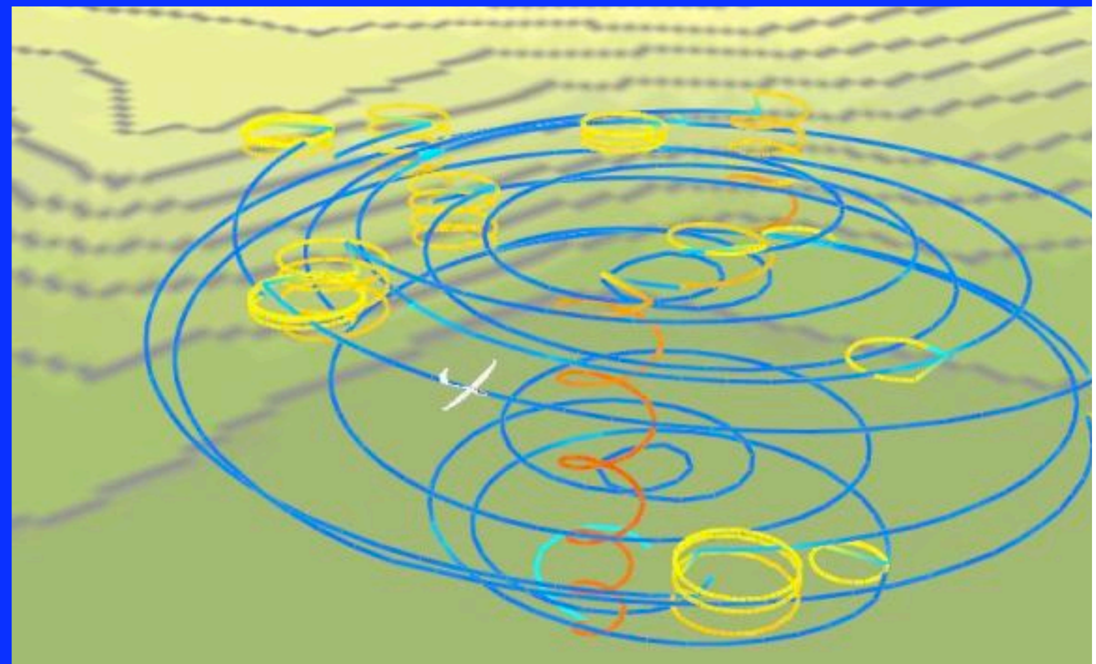
An Analytical Thermal Model for Autonomous Soaring Research



Michael Allen, NASA DFRC

SSA\SHA Western Workshop, Tehachapi 2004

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Purpose

- Purpose of thermal model is to enable research on autonomous soaring for small UAV aircraft.
- Autonomous soaring is a biologically inspired technology.
- Simulation results show that the duration of a small UAV can be extended from 2hr to 12hr.

Skylark left; Seagull right

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Approach

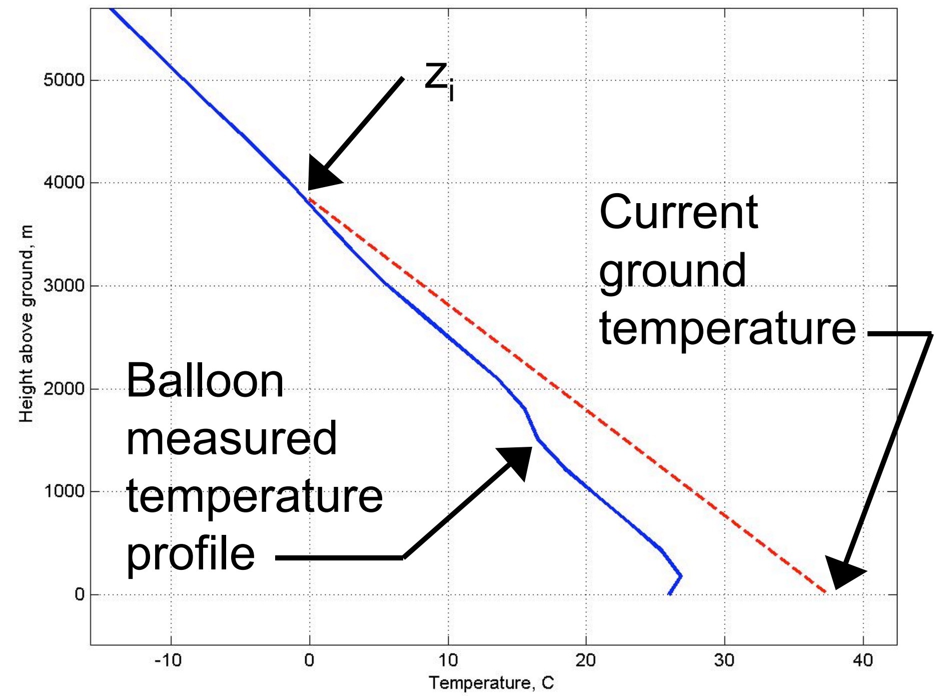
- Calculate convective layer scaling parameters, w^* & z_i, for each day during 2002 using measured surface and balloon data taken at Desert Rock, NV.
- Create test point matrix of scaling parameters.
- Use published equations to calculate updraft velocity, thermal radius, spacing, and shape from w^* & z_i.

SURFRAD Data

- Location: Desert Rock, NV
- Ground Instrumentation:
  - Radiometer platform
  - Met tower
  - TSI
  - Solar tracker
  - Sampled every 3min
- Rawinsonde balloons
  - Launched every 12hr
  - Pressure, Alt, temp, dew pt., wind

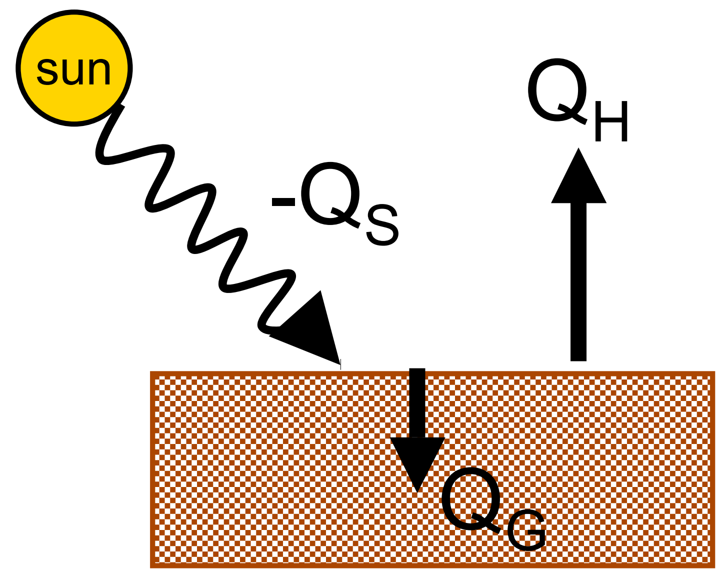
Convective Layer Thickness

- Convective layer thickness (z_i) from surface data and early morning sounding.
- z_i = intersection of (surface temp*DALR) and balloon temperature profile



Surface Heat Budget

$$\tilde{Q}_H = \frac{\hat{a}(-Q_S + Q_G)}{(1+\hat{a})}$$



β = Ratio of sensible to latent heat flux = 5

- Q_G = Surface heat flux = $0.1*Q_S$

Surface Virtual Potential Temperature Flux

$$Q_H = \frac{\tilde{Q}}{\rho * Cp}$$

$Q_{ov} = Q_H .* (1 + .61 * r)$ units: (Watts/m^2)

r = mixing ratio

Convective Scaling Velocity

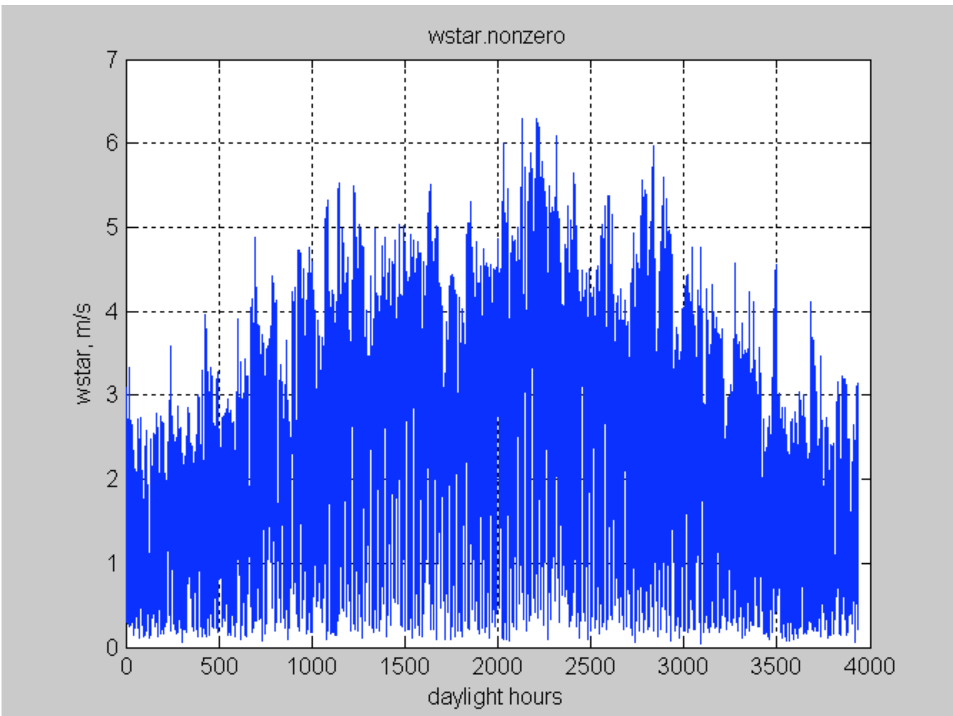
$$w^* = \left(Q_{OV} * zi * \frac{g}{\theta_o} \right)^{\frac{1}{3}}$$

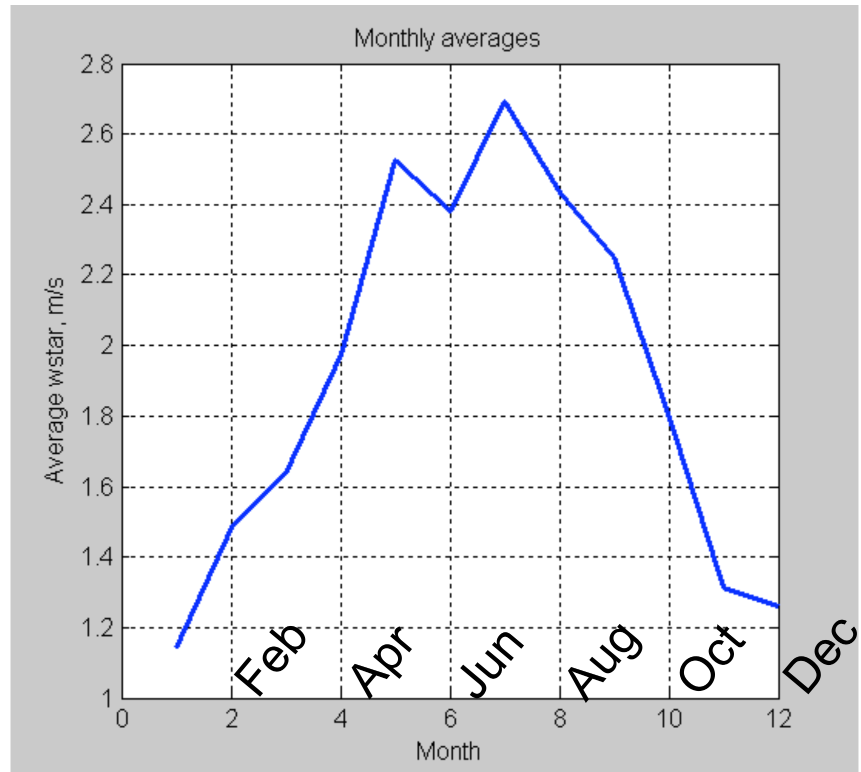
- Equation used by Lenschow to relate updraft measurements to atmospheric conditions.
- w* is the main driver of updraft velocity in the thermal model.

Other calculations

- If wind > 25kt, w^* is set to zero.
- Sunrise & sunset times were used to define local time.
- Calculations were made every 3 minutes.

Yearly trends





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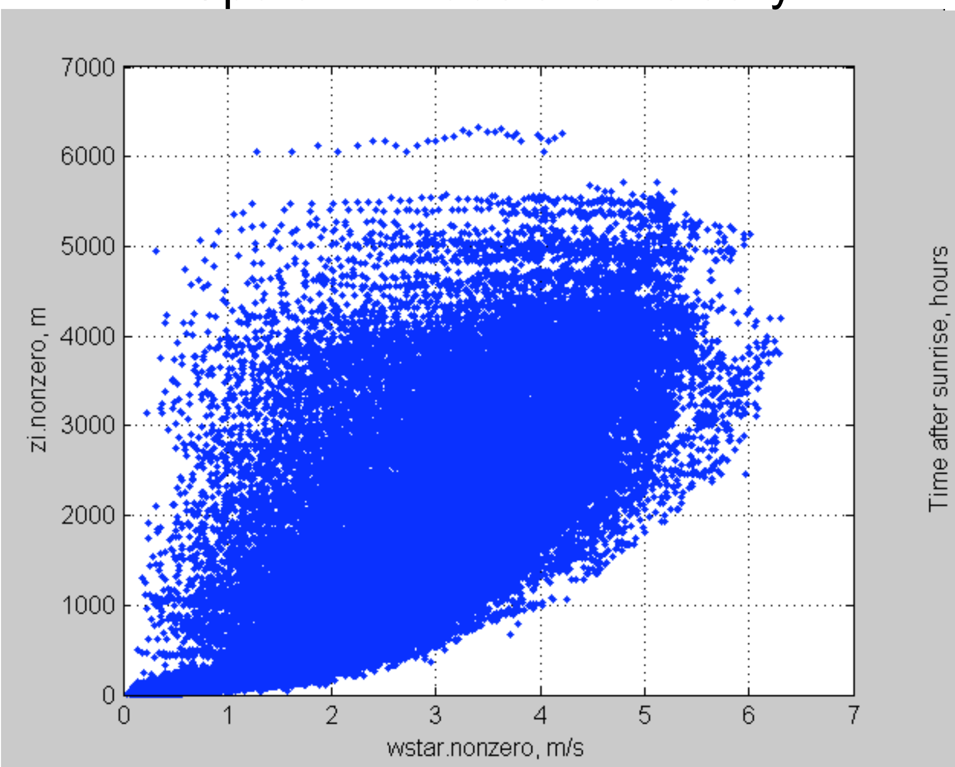
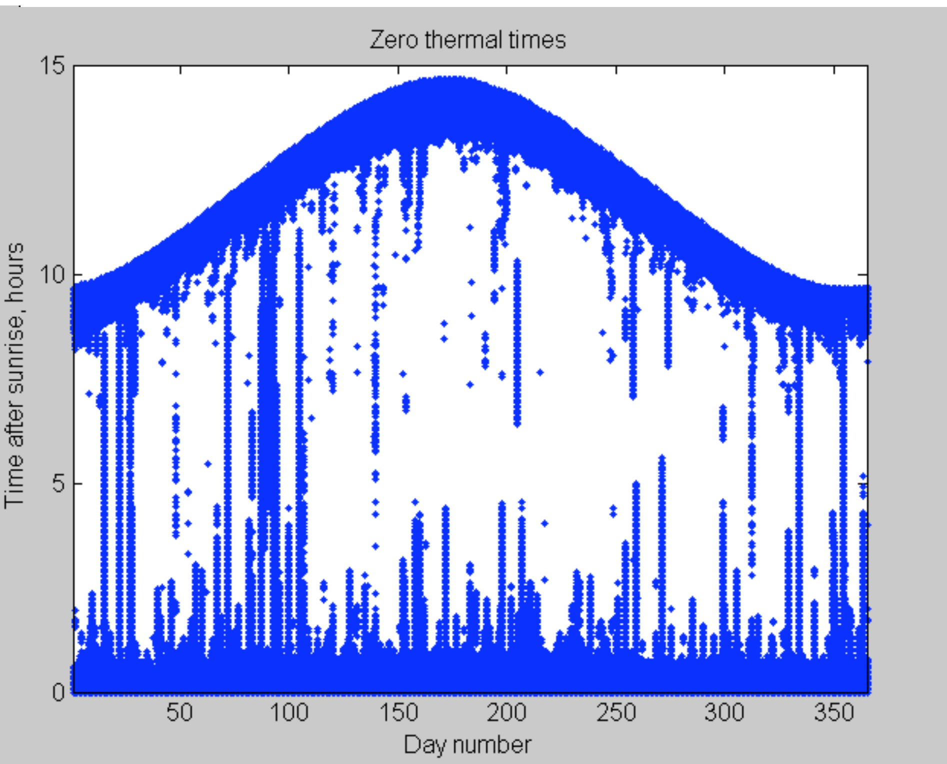
Scale Factors

Updraft Altitude and Velocity



Times When no Thermals Existed



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Scale Factor Test Matrix

- Statistics were used to resolve data into 15 updraft scale combinations that represent yearly and daily variations in thermal strength and height.

	w^*	z_i = -1σ	z_i = mean	Zi = +1σ
w^* = -2σ	0.46	25.6	53.6	97.4
w^* = -1σ	1.27	150	210	1007
w^* = mean	2.56	767	1401	2319
w^* = +1σ	4.08	2134	2819	3638
w^* = +2σ	5.02	2913	3647	4495

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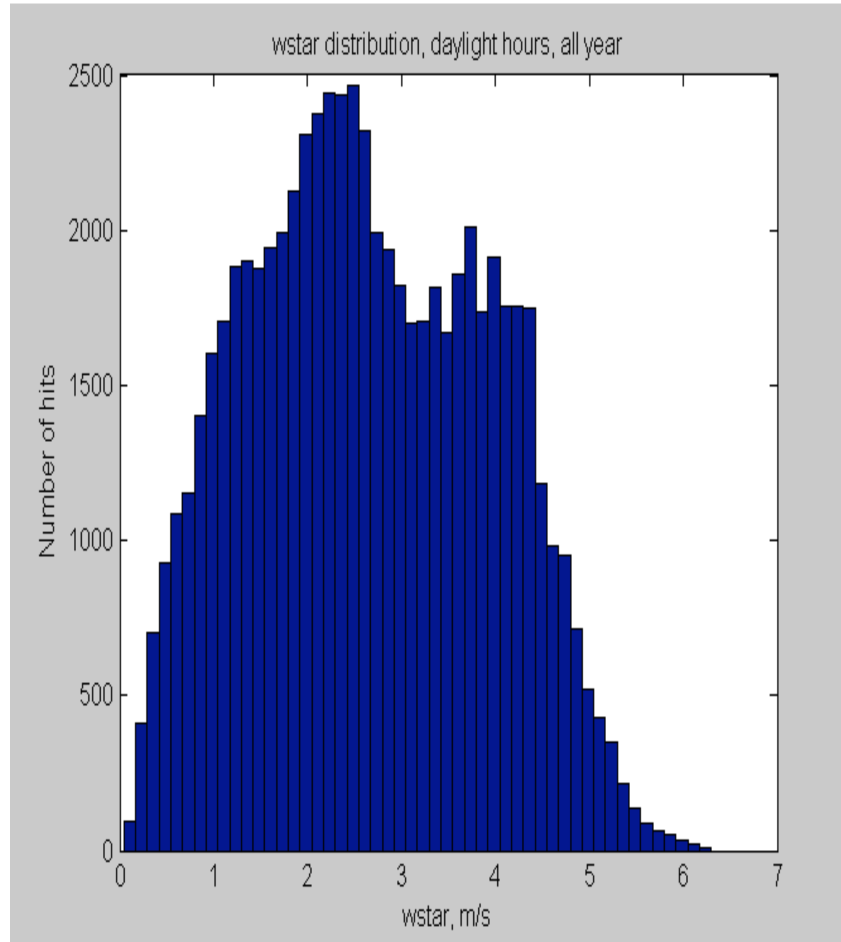
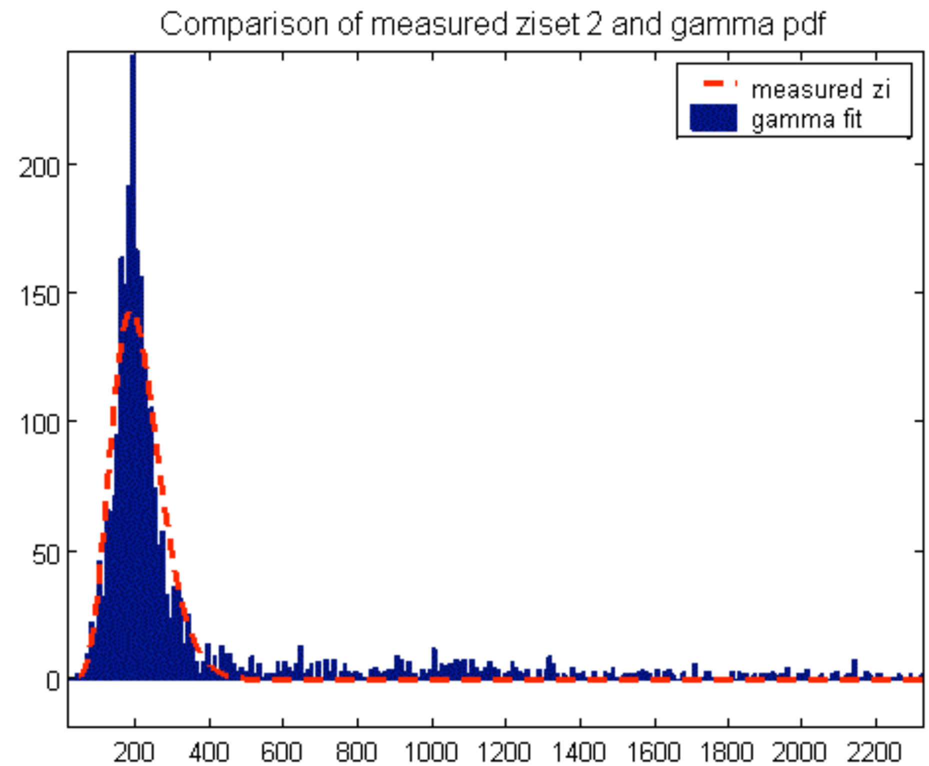
Statistical Model

- Gaussian fit of w*
  - Mean=2.65
  - Stdev=1.26
  - Maximum=6.3
  - -2σ=.13, -1σ=1.4
  - 1σ=3.9, 2σ=5.2
- Percentile method
  - -2σ=.46, -1σ=1.3
  - ‘mean’=2.56
  - 1σ=4.1, 2σ=5.0



Statistical model

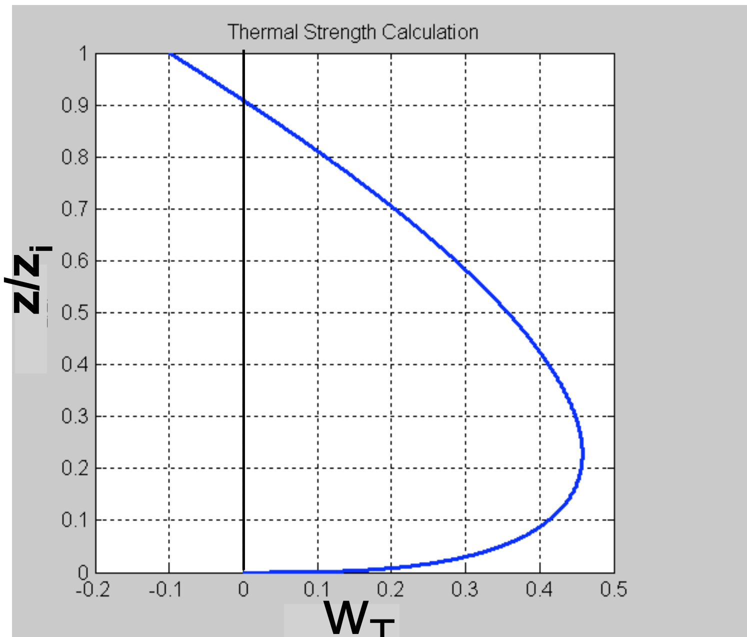
- Zi fits gamma probability distribution function.
- Gamma coefficients used to get -1sigma, center, and +1sigma points.



Updraft Strength Calculation

$$\overline{w}_T = w^* \left(\frac{z}{zi} \right)^{\frac{1}{3}} \left(1 - 1.1 \frac{z}{zi} \right)$$

- Lenschow, “The Role of Thermals in the Convective Boundary Layer”
- Data taken from flights over East China Sea during AMTEX experiment. Equations are similar to those produced from Colorado flights by the same researcher.



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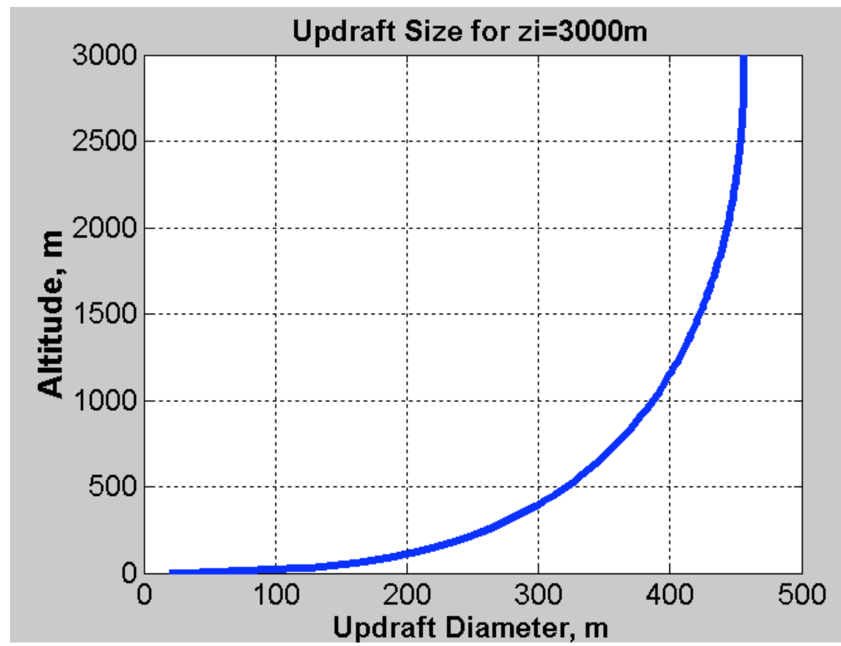
Updraft Diameter

$$\text{Dia} = \begin{cases} 0.203\left(\dfrac{z}{zi}\right)^{\frac{1}{3}}\left(1-.25\dfrac{z}{zi}\right)*zi & \text{for Dia} > 20\text{m} \\ 20\text{m} & \text{else.} \end{cases}$$

- Equation was taken from Lenschow's report.
- Rapidly changing updraft size at lower altitudes is likely due to updraft merging.



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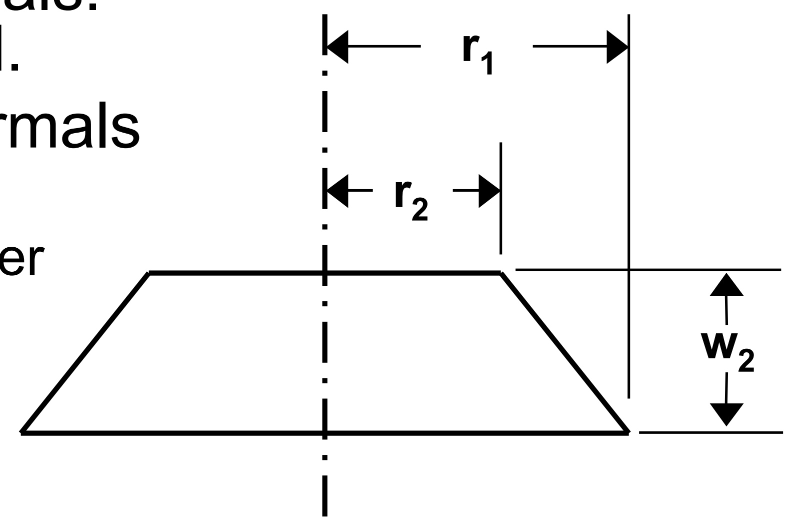
Updraft Shape

- No shape will capture real thermals. Range of shapes must be tested.
- Konovalov shows 2 types of thermals from flight data
  - Small diameter = most lift is at center
  - Large diameter = wide lift region
- I fit this data to a rotated trapezoid function
- Trapezoid parameters are calculated to fit Konovalov data and have average updraft velocity w_T.
- w_2 is calculated to give the correct average updraft velocity.

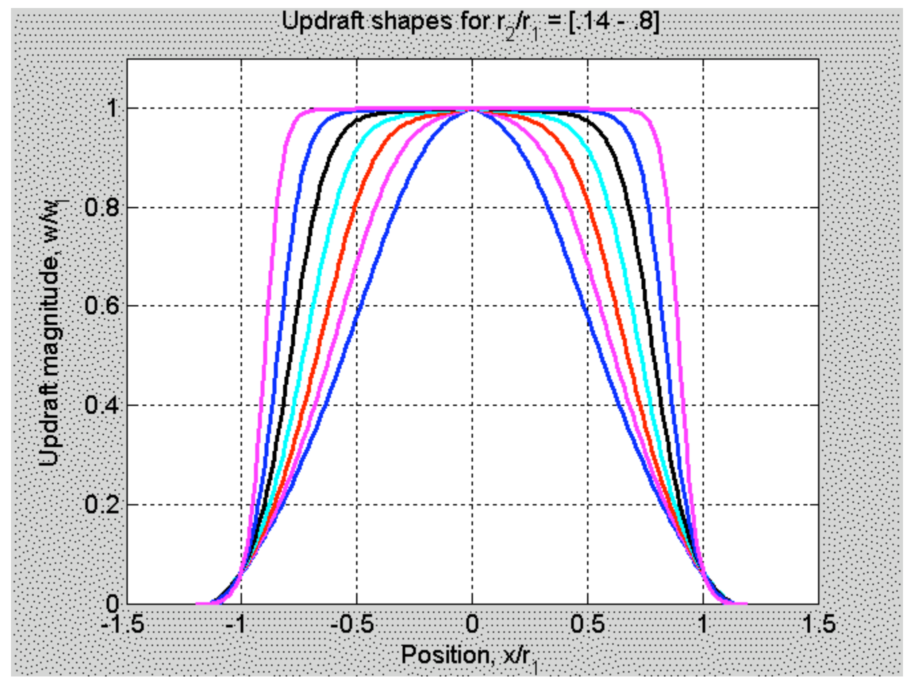


$$w_2 = \frac{\overline{w} * r_1^2}{\frac{r_2^2}{2} + \frac{1}{r_1 - r_2}\left(\frac{r_1^3}{6} - \frac{r_1 r_2^2}{2} + \frac{r_2^3}{3}\right)}$$

Smoothed Updraft Shape

- Smoothed updraft shape was determined by fitting Konovalov's data to a modified bell function.

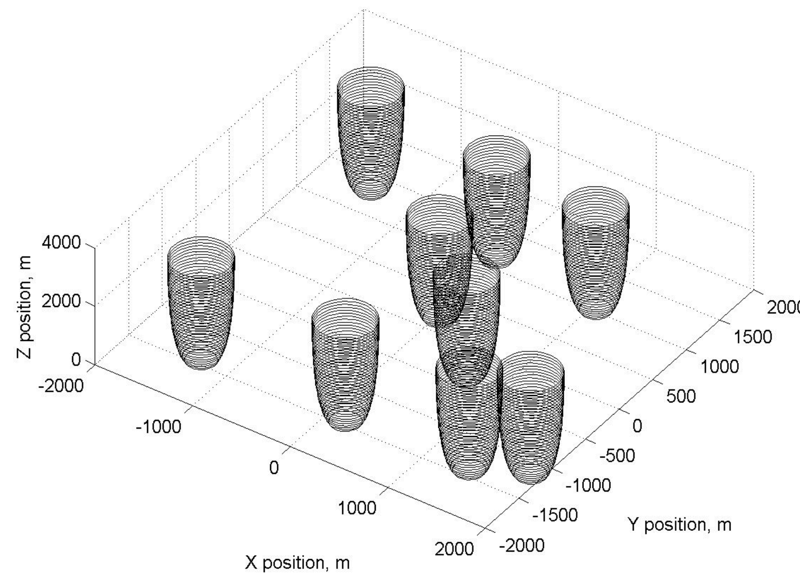
$$w = w_2\left(\frac{1}{1+\left|ka*\frac{x}{r_1}+kc\right|^{kb}}+kd*\frac{x}{r_1}\right)$$



r_2/r_1	ka	kb	kc	Kd
0.14	1.5352	2.5826	-0.0113	0.0008
0.25	1.5265	3.6054	-0.0176	0.0005
0.36	1.4866	4.8354	-0.0320	0.0001
0.47	1.2042	7.7904	0.0848	0.0001
0.58	0.8816	13.972	0.3404	0.0001
0.69	0.7067	23.994	0.5689	0.0002
0.80	0.6189	42.7965	0.7157	0.0001

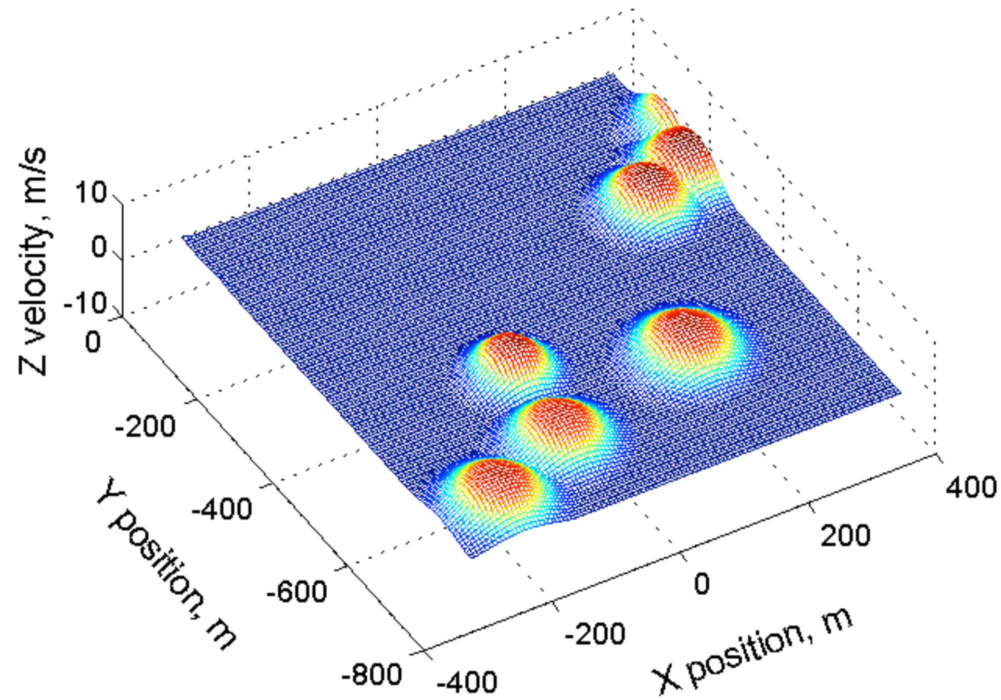
Updraft Spacing

- Actual updraft spacing depends on altitude with distant spacing at high altitude.
- Number of thermals along a line of length z_i is 1.20 at average altitude.
  - If z_i=1000ft and you fly a distance of 1000ft, you will encounter 1.2 thermals.



Environment Sink

$$w_e = \frac{-w_T N\pi\left(\frac{\mathrm{Dia}}{2}\right)^2}{X * Y - N\pi\left(\frac{\mathrm{Dia}}{2}\right)^2}$$



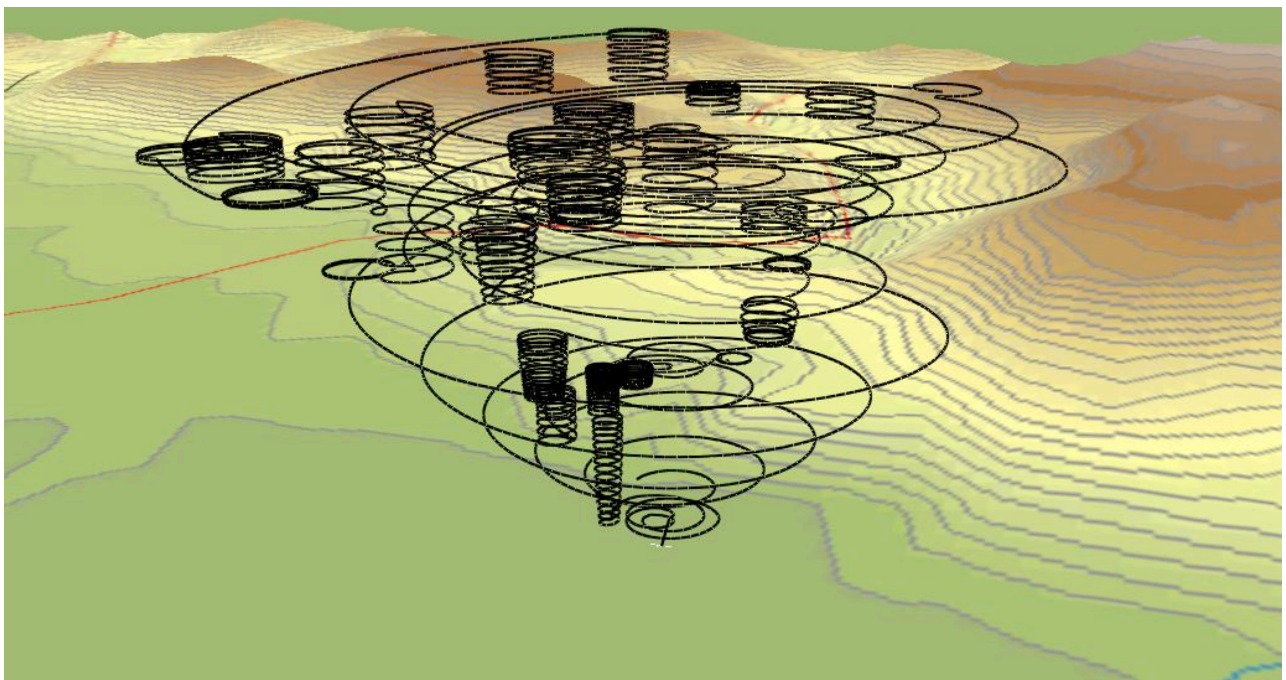
- Determined from conservation of mass.
- Sink is applied evenly to entire test space.
- Updrafts are scaled to give smooth transition from sink.

Updraft Lifespan

- Updraft lifespan is set to 20 minutes in this model. Various lifespans should be used for design and simulation.
- Thermal duration estimates:
  - 6-10 minutes (Pagan)
  - 5-15 minutes (Stull)
  - 5-20 minutes (Woodward)
  - 20-30 minutes (Hardy & Ottersten)

Autonomous Soaring Research

- UAV is “flown” each day using Desert Rock data from 2002.
- Loiter mission was used.



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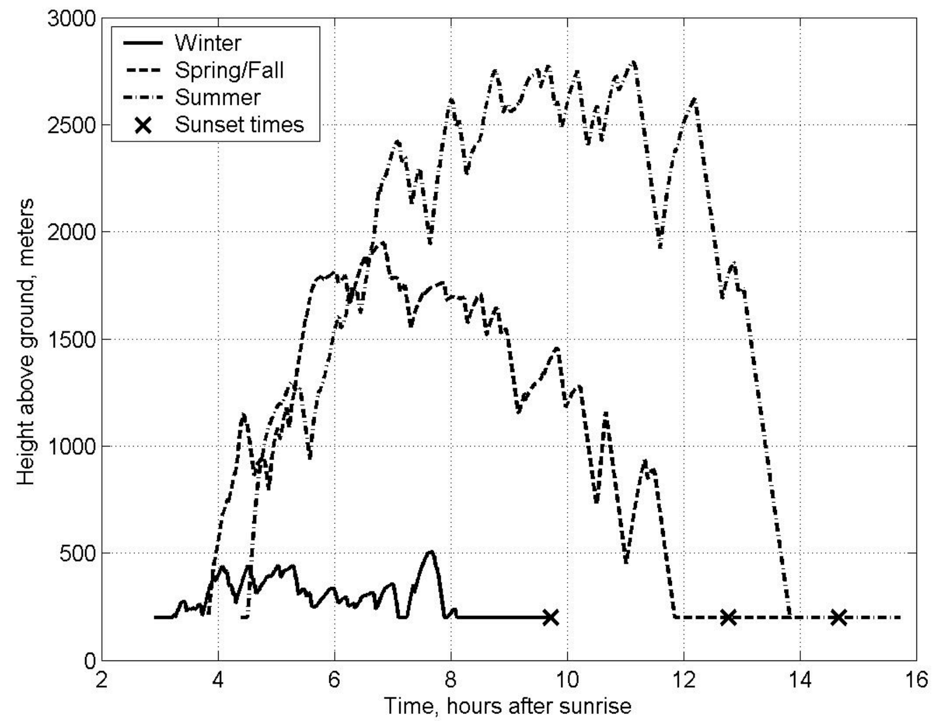
Autonomous Soaring Research

- Time-histories show large variation with season.
- Maximum Duration
  - Winter = 7hr
  - Summer = 12hr
- Complete results to be presented at January 2005 AIAA ASM conference.



Planned Flight Test

- Initial checkout flights in September will use standard autopilot software.
- Research flights with new software are planned for next spring.
- Initial objective is to demonstrate autonomous soaring.

Piccolo Autopilot
Weight: 9oz
Processor: mpc555
Instrumentation:
- 3 accelerometers
- 3 rate gyros
- GPS
- static pressure
- dynamic pressure

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Questions?

BACKUP SLIDES

Mixing Ratio

```
%sat pres. (mb)
 es=6.112*exp((17.67*ground.temp)./(ground.temp+243.5));

%vapor pres (mb)
 e=ground.rh.*es/100;

%mixing ratio (g/kg)
 r=622.0*(e./(ground.pressure-e));
```