Comparative Statistical Analysis of Soaring Competitions

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(Some) history:

Pre flight recorder: updraft maps (Germany: Müller/Kottmeier, Kreipl, Frettloh)

Post flight recorder I: Obvious application – "hot spots"

Examples: Polyteknisk Flyvegruppe Kopenhagen, Termikanalyse
            (www.pfg.dk/termikanalyse)
            Akaflieg Frankfurt LIFT project
            (Aerokurier 10/03, www.akaflieg-frankfurt.de)
            Track2Thermic (www.friulano.it/t2t.htm)
            Augustin et al.: "Thermal Updraft Maps for Gliders", Tuesday, 10.30

Do they exist in unstructured terrain?
Influence of day time, weather?
Three-dimensionality (x, y depend on z)?

Post flight recorder II: Second thought – Characterize pilot's usage of air

Speed to fly?      Aligned lift?      Potential flight distances?
Utilize the enormous amount of flight recorder data

Convert data string to 5-dimensional flight vector $V(t, y, x, h, w=\frac{dh}{dt})$

B14 0023 513 660 7N012 451 93EA016 98018 100 020 817 300 8
B14 0047 513 651 4N012 461 59EA016 79017 800 002 071 690 10

14.0064, 51.6101, 12.7532, 1698, -2.67
14.0131, 51.6086, 12.7693, 1679, -0.79

Beware! Air is not systematically sampled.
FR data reflect meteorological conditions filtered by pilot's response and external constraints (e.g. airspace regulations).

Having this in mind, what are possible
1) relevant (desired) results?
2) good source data?
Desired results: (A few) questions – what do we want to know?:

- What altitude band is utilized in "real" soaring?
  relevant for PFD calculations
- How does updraft strength vary?
  in dependence of time, altitude, geographical position,
  statistically (from updraft to updraft)
- Are there correlations between components of the 5D vector?
  \( w(h) \) – validity of speed to fly theory
  \( h_{\text{max}}(t) \) – forecast verification
  \( w(h_{\text{max}}) \) – relevant for PFD calculations

Some general answers:

- Distributions of vector components \( f(v_i) \)
- Correlations between vector components \( v_j(v_i) \)
  and related quantities (mean values, maximum values…)
Source data:

1) Online Contest (OLC) – www.onlinecontest.org
   Advantage: Most complete data set available
   Drawbacks: Restricted Access
               Huge variation of terrain and weather
               Ill-defined pilot strategy (from student to world champion)

2) Competition flights
   Advantages: Open access
               Well-defined pilot strategy
               Well-defined terrain and weather conditions
   Drawback: Less data available
Competition data pre-treatment

removal of pre-start and post-finish data
Competition data pre-treatment
removal of pre-start and post-finish data
Analyzed competitions (2007):

1) Lilienthal Glide, Lüsse, Germany, July 14 to 27
   97 competitors
   July 16, 23, 26
   254 flights
   127,000 data points

2) European Gliding Championships, Issoudun, France, Aug 6 to 19
   91 competitors
   August 9, 12, 13, 16, 18
   386 flights
   177,000 data points

3) Junior World Gliding Championships, Rieti, Italy, July 28 to Aug 11
   53 competitors
   July 29, 30, August 4, 6, 7
   221 flights
   95,000 data points
Basic results – tracks – y(x):

well defined geographical area with homogenous sampling

Lilienthal Glide
Basic results – variograms – w(t):

vertical speeds
Lilienthal Glide

![Vertical speed graphs](image-url)
From variograms $w(t)$ to vertical speed distributions $f(w)$:

projection of variogram onto $w$ axis
Vertical speed distributions $f(w)$ can be fitted to two Gaussian normal distributions, one representing climb, one representing sink.

$s(x) = y_0 + \frac{A}{w \sqrt{2 \pi}} \exp\left(-\frac{2((x-x_c)/w)^2}{1}\right)$

$R^2 = 0.98362$

$y_0 = 0 \pm 0$

$x_{c1} = -1.20356 \pm 0.032$

$w_1 = 1.8049 \pm 0.06227$

$A_1 = 4233.54432 \pm 136.98323$

$x_{c2} = 1.39927 \pm 0.03624$

$w_2 = 1.68247 \pm 0.06859$

$A_2 = 3357.71918 \pm 134.48225$

Lilienthal Glide, 2307
Climb and sink vertical speed distributions are general features

Rieti

ISSoudun
Vertical speed distributions - Summary:

<table>
<thead>
<tr>
<th></th>
<th>day</th>
<th>climb center, m/s</th>
<th>climb HWHM, m/s</th>
<th>sink center, m/s</th>
<th>sink HWHM, m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Issoudun</td>
<td>09.08</td>
<td>1.25</td>
<td>1.14</td>
<td>-1.02</td>
<td>0.77</td>
</tr>
<tr>
<td>Issoudun</td>
<td>12.08</td>
<td>1.29</td>
<td>1.07</td>
<td>-1.20</td>
<td>1.09</td>
</tr>
<tr>
<td>Issoudun</td>
<td>13.08</td>
<td>1.32</td>
<td>1.12</td>
<td>-1.25</td>
<td>0.98</td>
</tr>
<tr>
<td>Issoudun</td>
<td>16.08</td>
<td>1.52</td>
<td>1.24</td>
<td>-1.19</td>
<td>1.13</td>
</tr>
<tr>
<td>Issoudun</td>
<td>18.08</td>
<td>1.34</td>
<td>0.99</td>
<td>-1.28</td>
<td>1.03</td>
</tr>
<tr>
<td>Rieti</td>
<td>29.07</td>
<td>1.98</td>
<td>1.65</td>
<td>-1.51</td>
<td>1.16</td>
</tr>
<tr>
<td>Rieti</td>
<td>30.07</td>
<td>1.54</td>
<td>1.10</td>
<td>-1.17</td>
<td>1.08</td>
</tr>
<tr>
<td>Rieti</td>
<td>04.08</td>
<td>1.36</td>
<td>1.22</td>
<td>-1.22</td>
<td>1.15</td>
</tr>
<tr>
<td>Rieti</td>
<td>06.08</td>
<td>1.55</td>
<td>1.41</td>
<td>-1.43</td>
<td>1.02</td>
</tr>
<tr>
<td>Rieti</td>
<td>07.08</td>
<td>1.90</td>
<td>1.60</td>
<td>-1.62</td>
<td>1.12</td>
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<tr>
<td>Lüsse</td>
<td>16.07</td>
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<td>1.14</td>
<td>-1.47</td>
<td>1.13</td>
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<td>Lüsse</td>
<td>23.07</td>
<td>1.40</td>
<td>0.99</td>
<td>-1.20</td>
<td>1.06</td>
</tr>
<tr>
<td>Lüsse</td>
<td>26.07</td>
<td>1.56</td>
<td>1.06</td>
<td>-1.31</td>
<td>1.10</td>
</tr>
</tbody>
</table>
Basic results – barograms – h(t):

altitude bands with maximum altitude determined as 99.75 percentile

Lilienthal Glide
From barograms $h(t)$ to altitude distributions $f(h)$:

projection of barogram onto $h$ axis
Altitude distributions $f(h)$.
Fitting is not as straightforward as in the vertical speed case.
Conditional analysis of altitude distributions $f(h)$.
Climb ($\Delta$) $f_c(h,w>0)$ vs. sink ($\nabla$) $f_s(h,w<0)$ altitude distributions.

Climb and sink altitude distributions are almost identical. Either there is no $w$-$h$ correlation (likely) or, if there is, it is identical for flight in climb and in sink (unlikely).
Conditional analysis of climb altitude distributions $f_c(h)$.  
Circling climb $f_{c}^c(h)$ (in thermals) vs. straight climb $f_{c}^s(h)$ (aligned lift)

- **Climb $f_c(h)$**: 
  - $w = \frac{dh}{dt} > 0$
  - $(dx/dh)^2 + (dy/dh)^2 \approx 0$

- **Sink $f_s(h)$**: 
  - $w = \frac{dh}{dt} < 0$

- **Total $f(h)$**: 
  - **Thermal/circling $f_{c}^c(h)$**: 
    - $w = \frac{dh}{dt} > 0$
    - $(dx/dh)^2 + (dy/dh)^2 \approx 0$
  - **Aligned lift $f_{c}^s(h)$**: 
    - $w = \frac{dh}{dt} > 0$
    - $(dx/dh)^2 + (dy/dh)^2 \approx 0$
Altitude distributions of thermal $f_c^c(h)$ (□) vs. aligned $f_c^s(h)$ (■) lift. Significant variations, aligned lift accounts for as much as 50% of total lift!
Description of circling climb altitude distributions $f_c^c(h,w>0)$.

If $w$-$h$ correlations are absent, $f_c^c(h,w>0)$ can be obtained by integrating over thermal entering and thermal exiting altitude distributions $f_{in}(h)$ and $f_{out}(h)$:

$$f_c^c(h) = \int_0^h \left(f_{in}(h') - f_{out}(h')\right) dh'$$  \hspace{1cm} (1)$$

Consequently, $f_{in}(h)$ and $f_{out}(h)$ can be obtained by differentiating $f(h)$:

$$\frac{df_c^c(h)}{dh} = f_{in}(h) - f_{out}(h)$$  \hspace{1cm} (2)$$

Alternatively, $f_{in}(h)$ and $f_{out}(h)$ can be directly obtained from identifying thermals from flight recorder data.

Both methods should give identical results!
Excellent agreement between altitude distributions \( f_c^c(h) \) obtained from flight recorder data (□) and from integration of eq. 1 (●).

![Graphs showing altitude distributions for Rieti and Issoudun with altitude, m on the x-axis and abundance, % on the y-axis.](image-url)
Altitude bands (of $f_c(h)$) utilized for circling in thermals

<table>
<thead>
<tr>
<th>day</th>
<th>$h_{\text{max}}$, m</th>
<th>$f_{\text{in}}$/${h_{\text{in}}}$, m</th>
<th>$f_{\text{in}}$ HWHM, m</th>
<th>$f_{\text{out}}$/${h_{\text{out}}}$, m</th>
<th>$f_{\text{out}}$ HWHM, m</th>
<th>$h_{\text{in}}$/h_{\text{max}}</th>
<th>$h_{\text{out}}$/h_{\text{max}}</th>
<th>$\Delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>09.08.</td>
<td>1778</td>
<td>Issoudun</td>
<td>787± 15</td>
<td>174± 21</td>
<td>1510± 16</td>
<td>196± 23</td>
<td>44.3%</td>
<td>84.9%</td>
</tr>
<tr>
<td>12.08.</td>
<td>1357</td>
<td>Issoudun</td>
<td>828± 63</td>
<td>165± 46</td>
<td>1016± 313</td>
<td>214± 115</td>
<td>61.0%</td>
<td>74.9%</td>
</tr>
<tr>
<td>13.08.</td>
<td>1698</td>
<td>Issoudun</td>
<td>836± 29</td>
<td>225± 28</td>
<td>1381± 35</td>
<td>256± 35</td>
<td>49.2%</td>
<td>81.3%</td>
</tr>
<tr>
<td>16.08.</td>
<td>1528</td>
<td>Issoudun</td>
<td>898± 18</td>
<td>201± 15</td>
<td>1279± 14</td>
<td>181± 11</td>
<td>58.8%</td>
<td>83.7%</td>
</tr>
<tr>
<td>18.08.</td>
<td>1539</td>
<td>Issoudun</td>
<td>780± 8</td>
<td>172± 10</td>
<td>1312± 8</td>
<td>189± 11</td>
<td>50.7%</td>
<td>85.3%</td>
</tr>
<tr>
<td>29.07.</td>
<td>3320</td>
<td>Rieti</td>
<td>1753± 21</td>
<td>199± 27</td>
<td>2926± 53</td>
<td>468± 75</td>
<td>52.8%</td>
<td>88.1%</td>
</tr>
<tr>
<td>30.07.</td>
<td>2248</td>
<td>Rieti</td>
<td>1549± 18</td>
<td>220± 21</td>
<td>2007± 10</td>
<td>160± 11</td>
<td>68.9%</td>
<td>89.3%</td>
</tr>
<tr>
<td>04.08.</td>
<td>2608</td>
<td>Rieti</td>
<td>1641± 15</td>
<td>132± 26</td>
<td>2083± 75</td>
<td>447± 85</td>
<td>62.9%</td>
<td>79.9%</td>
</tr>
<tr>
<td>06.08.</td>
<td>3039</td>
<td>Rieti</td>
<td>1630± 68</td>
<td>370± 84</td>
<td>2670± 73</td>
<td>408± 93</td>
<td>53.6%</td>
<td>87.9%</td>
</tr>
<tr>
<td>07.08.</td>
<td>3317</td>
<td>Rieti</td>
<td>1896± 21</td>
<td>221± 28</td>
<td>3052± 29</td>
<td>284± 38</td>
<td>57.2%</td>
<td>92.0%</td>
</tr>
<tr>
<td>16.07.</td>
<td>2777</td>
<td>Lüsse</td>
<td>1469± 13</td>
<td>453± 20</td>
<td>2206± 28</td>
<td>550± 43</td>
<td>52.9%</td>
<td>79.4%</td>
</tr>
<tr>
<td>23.07.</td>
<td>1831</td>
<td>Lüsse</td>
<td>950± 5</td>
<td>265± 6</td>
<td>1346± 7</td>
<td>288± 10</td>
<td>51.9%</td>
<td>73.5%</td>
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<tr>
<td>26.07.</td>
<td>1970</td>
<td>Lüsse</td>
<td>1187± 6</td>
<td>281± 8</td>
<td>1625± 6</td>
<td>240± 7</td>
<td>60.3%</td>
<td>82.5%</td>
</tr>
</tbody>
</table>
Result corroborated by absence of w-h correlation.

Mean vertical speeds (black) are essentially independent of altitude. In contrast, maximum and minimum vertical speed values (blue) occur at medium altitudes.
Adding temporal resolution. Vertical speed distributions

Lilienthal Glide 1607

<table>
<thead>
<tr>
<th>Vertical Speed, m/s</th>
<th>Abundance, arb. units</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>16.00</td>
</tr>
<tr>
<td>1</td>
<td>15.30</td>
</tr>
<tr>
<td>2</td>
<td>15.00</td>
</tr>
<tr>
<td>3</td>
<td>14.30</td>
</tr>
<tr>
<td>4</td>
<td>14.00</td>
</tr>
<tr>
<td>5</td>
<td>13.30</td>
</tr>
<tr>
<td>6</td>
<td>13.00</td>
</tr>
<tr>
<td>7</td>
<td>12.30</td>
</tr>
<tr>
<td>8</td>
<td>12.00</td>
</tr>
</tbody>
</table>
Adding temporal resolution. Altitude distributions.

2607  Lilienthal Glide

0 500 1000 1500 2000

altitude, m

abundance, arb. units

0 1000 2000 3000 4000

abundance, %

16.00 15.30 15.00 14.30 14.00 13.30 13.00 12.30 12.00
Conclusions - Outlook

Methodical comments:
Powerful method for analyzing interplay of weather conditions with pilot strategy.
Careful choice of data set is important: Homogenous pilot mixture!
Good statistics require at least 40,000 data points/day (Rieti was too small.)

So far:
Mean climb and altitude are uncorrelated for all studied cases!
Method allows distinction between aligned lift and circling in thermals.
Aligned lift plays a major role in flat terrain as well as in mountains.
Aligned lift can account for more than 50% of total lift.

To come:
More competitions, more data: Assessing the role of aligned lift.