ParaglidingNet: A Sensor Network for Thermal Research

Master Thesis

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The sensor network provided by paragliding pilots flying cross-country competition and participating voluntary holds great potential. Flight logs run through several correcting algorithms in order to overcome the wide range of data quality. Corrected flights are analyzed for thermals and theire corresponding triggers are found. It is shown that thermal triggers shape areas and not points. The problem of the uneven flight distribution is solved by the use of knowledge maps ending up with raster-based time-dependant thermal probability maps. They are published in various, intuitive formats and perform great in practice, supporting paragliding pilots in flight preparation and analysis.

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1 Introduction

The majority of recent research in sensor network focuses on deployment of a series of small-scale sensors. Problems of low power and self organization have to be solved. Nodes are either physically placed or distributed randomly by the owner of the network. These networks offer interesting challenges for researchers but the public does not directly benefit.

Human centric networks are the new way to go, measuring the surrounding of each individual. These mobile wireless sensor networks currently mainly aim at cell phones and cars as their nodes, in order to measure for example traffic or noise. [1, 2]

Paragliding is not only a recreational sport, it also allows for competitions such as acrobatics and cross-country flying. Portable GPS recorders were first used in gliders and later in paragliding competition cross-country flights, too. By now, these devices are affordable and portable even by casual paragliding pilots.

International competitions with daily highscores are held on public websites allowing everybody to contribute without paying a fee. The only thing pilots have to do in order to participate is uploading their flight logs. The recording become public property and are mainly used to rate flights in order to make them comparable. Pilots participate voluntarily because of highscores and to have a personal flight journal. Therewith they are automatically participating in this sensor network.

Most networks based on voluntary participation are dependent on people interested in the specific project out of personal or financial interest. Normally, a participatory system design therefore has to focus on providing tools assisting participants in contributing verified data. [3, 4] In the current scenario, every pilot attending the competition, automatically delivers verified position data of its flight. Pilots pay for the sensor, partly enhance data quality and make it public property by uploading it. In return each flight gets rated, appears on a highscore list and can easily be viewed online. So the raw GPS data is already present awaiting further use and the most common problem of recruiting volunteers was never even encountered.

Paragliding as well as other unmotorized aircrafts use thermals in order to gain height. Long distances can be reached by flying from thermal to thermal. For cross-country pilots it is crucial to find the next thermal, even though thermals can not directly be seen.

Besides indicators such as cumulus clouds or flying birds, experienced pilots have advantages because they already know good thermal spots. I, myself am a young and addicted cross-country pilot, was impressed by this skills ever since and the idea to put this information in maps was born quickly.
There are some approaches to generate thermal maps based on elevation and soil properties as well as pin based approaches generated out of flight data (presented in Section 2.4). However, uploading flight logs to community websites became popular a few years ago and is growing ever since. So this is one of the first sensor networks consisting of thousands of nodes with hundred thousands of flights. So the opportunities of this database are yet unknown and its possibilities rarely used.
The goal of this work is to use all paragliding flights available in Switzerland to create a maps of thermals. Given weather conditions, such as wind direction, strength and time, it is expected for thermals to cluster at specific locations. These hotspots are expected to be seen by analyzing the set of flights for thermals. To facilitate the study of unknown areas and analysis of flights, these maps have to be published in an intuitive format for pilots. So the circle is closed and the pilots voluntarily uploading flights even gain further use by getting back additional information to improve their flights even more.

2 Thermal Basics

This chapter covers some basics of thermal theory important for this work. Locations favoring the appearance of thermals are described as well as the impact on the characteristics of paragliding flights. Finally existing projects predicting thermals on a high spatial resolution are presented. Some explanations about weather parameters can be found in Appendix A.2.

2.1 Thermal Structure

There are different descriptions of the thermals shape in literature because the authors look at various different types of thermals. Some observe the thermal motion in fluids and make assumptions on the moving in the atmosphere. [5, 6] Others use radars to measure the real motion of the air in clouds to come up with new models. [7] And another more practically oriented group consists mainly of glider pilots and their description of thermals in flight based on experience. [8, 9, 10, 11, 12]

The theoretic motion of an isolated thermal is like a vortex ring. The strongest updraft is found in the center of the thermal whereas outside the cold air sinks back down. The sinking area is much larger than the thermal, thus the downwards velocity around the tube is smaller than the updraft in the cap. As the thermal rises, its radius increases by an angle of about 15° along the cone. In the border area (about 15-20% of the radius), mixing of the air masses occur. This area has a high variance in vertical velocity meaning turbulences, swirls and eddies.

In reality there are numerous forms of thermals. They range from long-time stable tubes to short lived pulsating and bubbling thermals. Under clouds even a mixing of thermal types are observed: small strong bubbles in a big plume or bubbles in bubbles and so on. High and stable thermals often evolve from multiple smaller thermals. These smaller thermals in the surface layer origin directly from the ground and are already used by paragliders to climb.

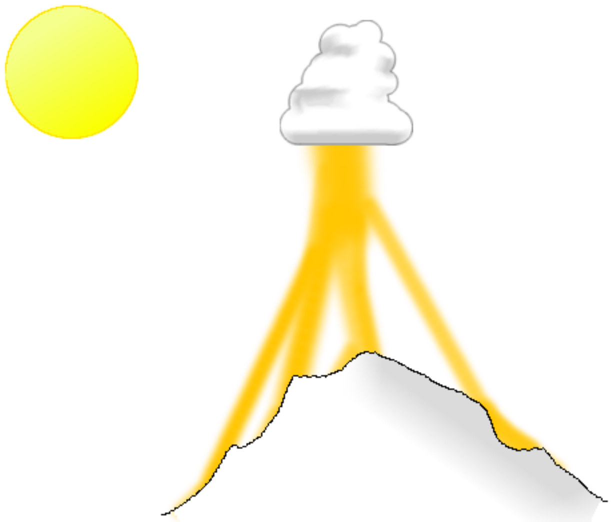

Figure 2.1: Schematic view of multiple thermal plumes merging into a big one. Each of the smaller thermals originates from its own trigger point on the surface.

Wind Offset

In flatlands with no stable trigger point, thermals are standing upright and travel with the wind. Thermals with a fixed origin are shifted with the wind as they rise (Figure 2.2). The shifting is relative to the wind speed and direction but not directly linked. The horizontal speed inside a thermal is normally less than the surrounding air. First, the rising air has its own momentum (initially zero at ground level) and global wind does not flow through the thermal but mostly around it. In wind theory, mean wind is known to increase logarithmically with height above ground. The logarithmic wind profile is valid in flatland and only used for the lowest 100 m. For the rest of the boundary-layer, a linear approximation should be used. [13] However most flights investigated during this work take place in mountainous areas where other effects like valley winds are of higher importance for the lower wind profile. Secondly most paragliding flights reach elevation much higher than 100 m above ground or if they come close to the ground it is near the top of a mountain. Thus and also for simplicity the offset of thermals is assumed to be linear, which is performing best in practice.

2.2 Thermal Triggers

According to given soil properties, air packages close to the ground heat differently. In order to favor appearance of thermals, air close to the terrain needs to heat as much as possible. Several surface characteristics have a positive impact: [8,10]

- The sunlight should strike the ground in a preferably right angle. This delivers the most energy per area. Slopes orthogonally exposed to the sun already show good thermal properties in early hours of the day or during winter months.
- The albedo of the surface should be as low as possible to absorb most of the energy. For example snow has a remarkably high albedo radiating most of the energy back to the atmosphere, which is one of the causes that snowfields do not heat over the

day. It is unlikely to find thermals over broad areas of snow. On the other side, a dark rock surface promises good thermal properties.

- The ground should be dry. Thus energy is not wasted for evaporation but directly heats the air close to the ground.

The described promotive soil properties often do not suffice to detach a heated air package from the ground. A disruption in the air masses is needed in order to overcome the surface tension and finally release the package. [11] There are uncountable types of potential thermal triggers and origins:

- Especially in mountainous areas topographic factors play the most important role. These are ridges, hilltops or simply the transition from a steep to a shallow slope.
- Also the transition from dry and warm fields to colder woodland can act as a thermal trigger.
- In particular in early spring, where the mountain tops are still covered in snow and the bottom of the valley is already clear, the snow line acts as a good trigger.
- Besides the listed passive triggers there are also active ones such as the moving shadow of a cloud or furthermore also a freshly mowed field. These factors are hardly predictable in static maps and only detected during flight.

A schematic trigger point, as it will be used during this work, is drawn in Figure 2.2.

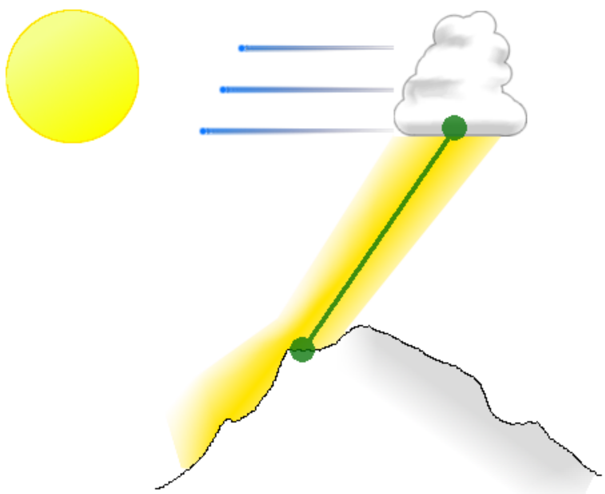

Figure 2.2: Schematic side view of a thermal (yellow) with trigger point (green thermal origin on the surface) and wind offset coming from the left.

2.3 Cross Country for Paragliders

Paragliders as well as other hang-gliders and gliders can travel huge distances without a motor. This is also called 'cross-country-flying' (XC). Different forms of ascending air currents are shortly presented and it is shown why paragliders rely upon thermals as their key updraft for example in contrast to gliders.

Thermal Flight

It takes time and skill to master thermal flying, but talented pilots are able to gain height even in very turbulent or light updrafts. To travel, a pilot first has to gain enough height in a thermal, and can then leave and reach the next available thermal. An ideal flight therefore forms a zigzag, altering from climbing in thermals to traversing to the next thermal. Paragliders can successfully circle in small thermals which gliders can only cut. The mean speed of the updraft obviously needs to be higher than the minimum sink rate of the paraglider in order to gain height.

Light Updraft

For gliders, it is also important to know the areas of light rising air, which can not be used to gain height but to increase gliding performance. Light updrafts increase also the gliding performance for paragliders but, as shown in the following example, this is a minor factor for cross-country flying. Gliders nowadays reach a minimum sink rate of about 0.5 m/s. If an area has light ascending air of 0.25 m/s on average, the gliders glide ratio is doubled from about 50 up to 100 (loosing 1 m in height results in 100 m horizontal distance). A paraglider with a glide ratio of 9 and a minimum sink rate of 1 m/s entering the same area increases its glide ratio up to 11.25. Normally this does not has a huge impact on overall flight performance.

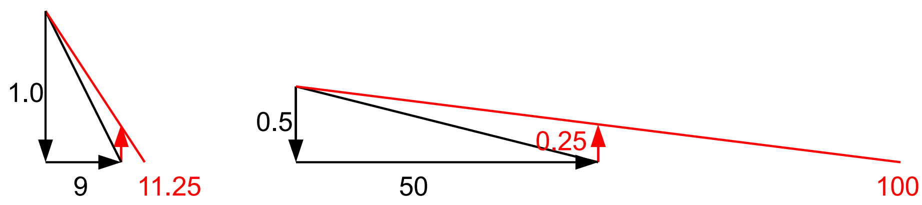

Figure 2.3: Impact of a light 0.25 m/s updraft in average on the glide ratio of a paraglider (left) and on the glide ratio of a glider (right). Black is the initial glide in stable air and red the one with the light updraft.

Ridge Soaring and Waves

Also dynamic hang winds are an important component for paragliding flights. This happens when a valley or a more global steady wind hits a slope, cliff or a dune. However a combination of soaring and thermaling is often seen. Such as starting with soaring in the valley wind with a smooth transition to thermaling as more hight is gained.
A good wind speed window for soaring is narrow. It ranges from having enough wind to not loose height to the maximum flight speed depending mainly on the paraglider. Even though in some cases remarkable distances can be reached, for example by ridge soaring along a coastline but pure soaring is primary used for local flights. For gliders, the wind speed window is much larger and they perform well in strong wind conditions. Wind waves on the lee side of a mountain range provide good conditions for long glider flights. For paragliders such harsh wind conditions are not flyable.

2.4 Existing Thermal Maps

Several different approaches for thermal maps exist nowadays. Earliest and still widely used source of information about thermals is told mouth-to-mouth. Senior pilots know good and bad thermal spots. The quality of this information differs from well known flight rules, to very subjective impressions. First real thermal maps were drawn by hand based on soil properties and vegetation. [14]
Since GPS track logs are widely available (at least for gliders), several fan projects were launched. Some of the these maps are presented here to give ideas and hints for new thermal maps for paragliders.

Lift

The academic gliding club of the Johann-Wolfgang-Goethe University of Frankfurt published a tool to generate thermal maps for Germany [15]. Thermal maps can be generated by defining map parameters such as the daytime interval, yeartime interval and minimum climb. Raster maps are generated dynamically with a Raster size of at least 2 km. The generated maps are based on glider flights uploaded to the OLC 2002-2003. The goal of the project was to find good regions for flights based on the input parameters, rather than identify actual thermal origins.

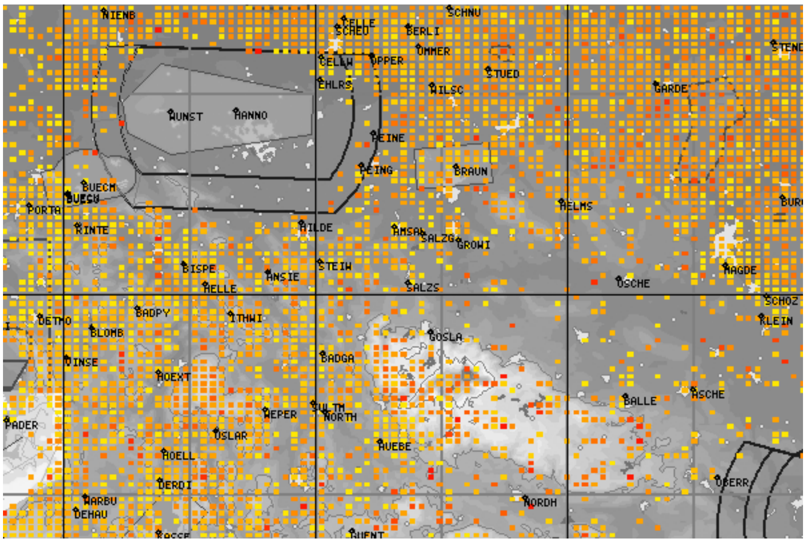

Figure 2.4: ©Akaflieg-Frankfurt: A dynamically created part of a thermal map showing southern Niedersachsen for spring 2003.

Track2Thermic (T2T)

Track2Thermic[1] provides a tool to analyze self made flights for thermals. A thermal trigger point is found by linear extension of an uplift. This key idea will be reused in this work but implemented completely different. Each thermal is classified by height, wind direction, climb strength and minimum height. Also little gaps in climbing are detected and stitched together. Finally each of these trigger points can be exported and used on a GPS during

[1] `http://www.friulano.it/t2t_eng.htm`, visited May 2010

flight. The project also provides a small basis database of trigger points mostly based on flights published on Online Contest 2002-2004 (see Section 3.2).

DHV-XC Thermik

On the official DHV-XC a cluster based thermal map is in use. Each detected thermal is somehow visualized by a marker. In order to reduce the amount of markers, thermals are clustered together if they are within a zoom-dependent radius. Theoretically this also allows live updates of the thermal sources.

TherMap

TherMap©[2] is a physically based thermal model. Solar radiation, calculated on basis of a digital elevation model, is used as a basis. Thermal maps are computed according to accumulated heat. This is influenced by approximations of a mean seasonal vegetation and snow coverage of an average year. Finally the heated air climbs along steep slopes until it reaches a shallow slope or snow (a trigger point). The resulting thermal pressure maps give detailed predictions of the local thermal potential.
An example map is show in Figure 2.5. These maps will also be used for comparison in Section 5.3.

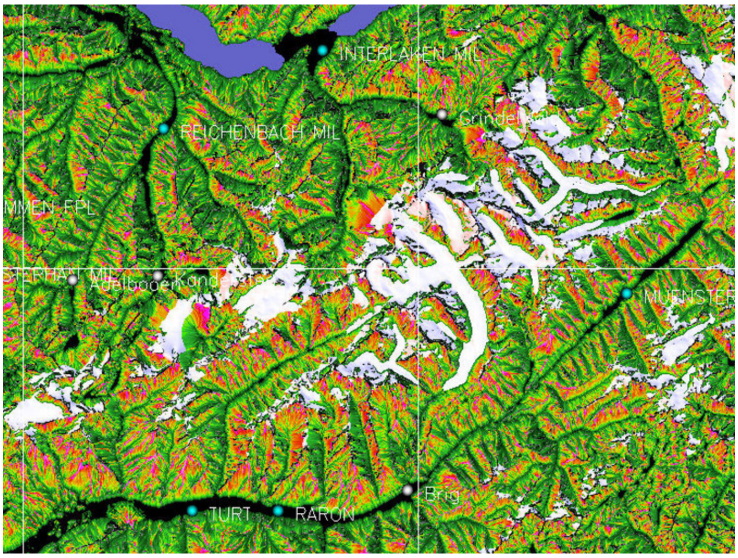

Figure 2.5: ©Dr. B. Sigrist: TherMap showing Wallis and Berner Oberland at first of August 13:00UTC.

[2] `http://www.aerodrome-gruyere.ch/thermap/`, visited May 2010

3
Data Processing

This chapter describes the path from the raw flight data to a a set of thermals. Recorded by a GNSS recorder during flight, transfered to a PC, uploaded to a community competition page, transformed by several cleaning and correction algorithms to be finally analyzed for thermals.

3.1 GPS Devices

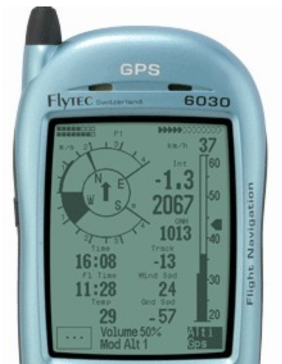

Figure 3.1: Flytec©6030

Various flight recorders are used. They range from simple hiking aids with low fixpoint resolution and GPS height only up to sophisticated multi-functional flight instruments. Because of this wide range of different recorders many different specialties and little bugs might occure.

3.2 Community Pages

At the time of this work, several online gliding competition webpages exist. Lots of these competition pages are very small and mainly designed for a single competition. Some others are very popular in a specific country but not widely known elsewhere. Currently the main pages in central Europe and especially the alps area are the following:

- xcontest [1]
- DHV-XC [2]
- Leonardo (Paragliding Forum) [3]
- Online Contest (OLC) [4]

OLC is the oldest one, founded in 1999 and offering competitions for gliders, hanggliders and paragliders. It was one of the first pages focusing not only on professionals, but on casual athletes, too. A handicap is applied to flights in order to compare their performance under unequal conditions and with different glider types. This also allows international competitions. The main focus of OLC remained on gliders (planes). Possible reasons are, that early generations of GPS recorders were easier to carry in a sailplane and it was more common for a glider pilot to afford it. Registration to the online contest free of charge was rather unusual at this time. Since 2002 DHV and SHV organized competitions in cooperation with the OLC. Handhold GPS devices became more and more popular and so the number of competitors increased.
Another project is Leonardo[5]. It is an open source server designed to show flights of paragliders. It became a large project with many features to satisfy the needs of paragliding pilots. There are options for easy flight analysis and scoring according to the OLC classes, as well as various statistics and highscores. Besides the international server, several country leagues host their own servers customized for their needs. All of these are linked together, forming the global XCnet. DHV is one of these nodes for example, since it separated from OLC in 2007. Since 2007 also xcontest plays an important role in therms of soaring sites (back then it was known under the name PGWeb). Because of technical problems also SHV and others were forced to look for another hoster and settled with xcontest. Nowadays, Leonardo and the xcontest servers are linked together forming a big worldwide paragliding competition platform. Also the community aspect plays an important role. Beside the tracklogs, pilots may describe their flight experiences and upload pictures whereas other pilots can comment on flights. Highscores for several competitions and classes exist for daily and seasonal time periods. This results in roughly 250'000 flights worldwide on xcontest from 2007 till 2009.

[1] `http://www.xcontest.org/`, visited May 2010
[2] `http://xc.dhv.de/`, visited May 2010
[3] `http://www.paraglidingforum.com/leonardo/`, visited May 2010
[4] `http://www.onlinecontest.org/`, visited May 2010
[5] `http://www.leonardoxc.net/`, visited May 2010

3.3 IGC

The gathered GPS tracklogs are stored in a well defined format, defined by the International Gliding Commission (IGC)[6]. [16] IGC is a subcomission of the Fédération Aéronautique Internationale (FAI) and is responsible for the worldwide gliding activities. This includes gliders as well as paragliders and hanggliders. A first revision was specified in March 1995 and was revised several times since. The FAI/IGC specifiactions define the worldwide used standard for recording and verification of gliding flights.
There exists various programs to transfer the flight from the flight recorders memory to a computer and store it as igc. Most manufacturer ship their own proprietary software along with the GPS but there exists also a lot of open source variants like GPSBabel[7] or the Firefox addon GiPSy[8] offering the possibility to upload flights directly to xcontest.
An igc file is text based and consist of several records, each on a separate line. The record type is specified by the first character of a line. Which records are actually included and in which order varies heavily depending on recorder and upload tool. The general structure is illustrated as an example in the following listing:

```
AFLY06054
HFDTE190809
HFFXA100
HFPLTPILOT:Max Muster
HFGTYGLIDERTYPE:Sigma 7
HFGIDGLIDERID:SHV0000
HFDTM100GPSDATUM:WGS84
HFGPSGPS:FURUNO GH-81
HFRFWFIRMWAREVERSION:3.28
HFRHWHARDWAREVERSION:1.00
HFFTYFRTYPE:FLYTEC,6030
HPTZNUTCOFFSET:2:00
I013638TAS
B1106124652811N00915653EA0248702677000
B1106154652811N00915653EA0248702677002
B1106184652811N00915653EA0248802677004
...
B1527514650135N00916832EA0100701104000
L   FlyChart
L   Version 4.52(41) TEST DEBUG, July 21th 2009
GBCCCF4B87139434A3D83DB03E4249406
G6298FB602F3AF4F1A53C5A7E81364CA2
G8A8E7B778F9D769D0054F75101ACCAE5
G0000000000000000BC000000000000
```

Listing 3.1: Sample igc file

The first line (A record) specifies the flight recorder by its manufacturer code. In this case its a widely used professional flight instrument from Flytec. Other flights were logged using a much simpler device. Next is the HFDTE record which defines the date and will

[6] http://www.fai.org/gliding/, visited May 2010
[7] http://www.gpsbabel.org/
[8] http://www.xcontest.org/gipsy/

be mentioned in Section 3.3.2. HFFXA defines a typical accuracy of a fixpoint before if is specially marked as error. However most manufacturer set this value much too high in order to be on the safe side, such that it can not be relied on to detect errors. Most of the time the accuracy is much higher due to good exposition of the flight recorder during flight. There are various different H records one can specify. Often these values are seen, but filled with garbage, because pilots do not care. If secondary information, such as glider type is needed it is taken from the community site instead. Because this is a rather advanced logging device, it defines an uncertainty for the GPS (in the I record), which is appended to the position record.
Next are all fixpoints (B record) which are further described in Section 3.3.1. A typical igc file holds 200 up to 10000 fixpoints. It follows an auto generated comment and finally the signature. Trusted flight recorders are certified by the IGC and are able to sign flights. This key is generated directly on the device and only verified flights can be used in competitions. Thus flights can hardly be faked and data integrity is guaranteed.

3.3.1 B Record

During this work mainly position records (B records) are of interest. B records are stored in the following format:
`B HHMMSS DDMMmmmN/S DDDMMmmmE/W V PPPPP GGGGG`

- HHMMSS: The time in UTC, when the fixpoint was recorded. Because of this format the accuracy is limited to full seconds.
- DDMMmmmN/S, DDDMMmmmE/W: Geographic latitude and longitude with an accuracy of a thousandth of a minute. If no fresh and valid position is available, the last valid position is used.
- V: This byte is set if no valid GPS coordinates are available and only the barometric height could be evaluated. This might be the case when the Sensor lost contact to a GPS satellite but not if the position is very inaccurate.
- PPPPP: The Barometric altitude in meters above ISO sea level of 1013.25hPa. Most used devices provide this information.
- GGGGG: The GPS altitude in meters above the WGS84 ellipsoid. This is available as soon as at least 4 satellites are visible.
- Additionally an accuracy estimation (FXA) could optionally be appended. Sadly only rarely used high-end logging devices are able to calculate this information and therefore it is not used for the time being.

As an example, the first B record of the sample igc file (line 14) can be read as follows: The fixpoint was taken at 11:06:12 UTC, which is 13:06:12 MEZS. The position is 46° 52.811’ north and 9° 15.653’ east. The ”A” stands for a valid GPS altitude and position. The barometric height is only 2487m whereas the GPS height is 2677m. The flight logger estimates the position to be very accurate.
The resolution of full seconds is a problem because some logging devices are recording with frequencies of two up to one second. Because of rounding to the next second, multiple fixpoints can fall into the same second. This would result in infinite speed between

those fixpoints. For paragliders such points are very near to each other (about 10 meters apart) and therefore the points can easily be merged.
Fixpoints which have the fix validity byte set are filtered out. One could try using only the provided altitude and interpolate position between valid fixpoints. But this procedure fails as soon the paraglider turns. Additionally we do not care too much about some single missing fixpoints because most of the time the GPS signal is available just one fixpoint later.
Where ever available, the barometric altitude is used. In normal cases this can be more accurate than the altitude provided by the GPS and it quickly reacts to small changes in height. This is important to the pilot and therefore most of the devices contain a barometric module. However the altimeter needs to be well calibrated before launch. If the pilot lacks in calibrating his device properly this has to be fixed as explained in Section 3.4. Some logging devices use both altitude informations in order to calibrate the barometric altimeter internally. This is the ideal case because the device calibrates itself independently after bootup and it can react to pressure changes of the atmosphere.

3.3.2 HFDTE Record

The date of the flight is only defined once per file since gliding flights can not go on on during the night. It has the following format:
`HFDTE DDMMYY`
By comparing the date record to the manually specified date, the pilot selected while uploading his track, it became obvious that it was often erroneous. About one third of the pilots simply do not care about the date on their devices. Therefore the date is completely ignored and the date specified on the community page was used instead.

3.4 GPS Track Correcture

The gathered tracklogs contain several kinds of errors. Some are introduced by faulty use of the device by the pilot but most are errors of the logger itself. The most frequent and also the most obvious error are GPS inaccuracies regarding position. Generally the pilot is well exposed to the satellites during flight, however the quality of the tracks varies.
One reason is that different devices are used, some of them tend to be more inaccurate than others. Other reasons are the storage location of the device and the recording frequency. The influence of the device type and the exposure is obvious. However recording frequency needs a closer look.

3.4.1 Logging Frequency

Normally the pilot can choose the logging interval manually but most GPS models measure position more frequent than it is stored. By just taking the mean of the measurements or even a more intelligent approach, small measure errors are likely to disappear. If the fixpoints are taken very frequently, these errors can directly be observed in the raw data. A simple smoothing filter in function of logging interval, smooths out many small spikes without loosing too much information. There are tracks with about one fixpoint every 30 to 60 seconds. No smoothing is required here but the fixpoints are very inaccurate and it becomes nearly impossible to, for example, detect circling in such a track. A second problem results from a high logging frequency where time is rounded (as mentioned in Section 3.3).

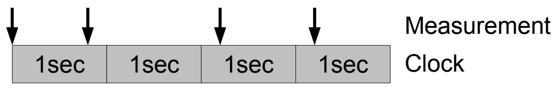

Figure 3.2: Sample measurements do not take place every full second.

Actually the igc file format is not adequate to be used with logging intervals near to a second because the logging format limits time resolution to full seconds. Additionally, GPS devices in use do not measure position in constant intervals and therefore fixpoints are just assigned to a near second. The problem of oversampling and uneven sampling intervals is illustrated in Figure 3.2.

3.4.2 Spikes and Trimming

Several data errors need to be corrected before the flight can be analyzed. Starting with the most obvious error: spikes. Spikes are short duration transients in position or altitude and occur frequently. Most of the time they occur at the beginning of the track during device boot up, but they can occur at any time during flight, too.

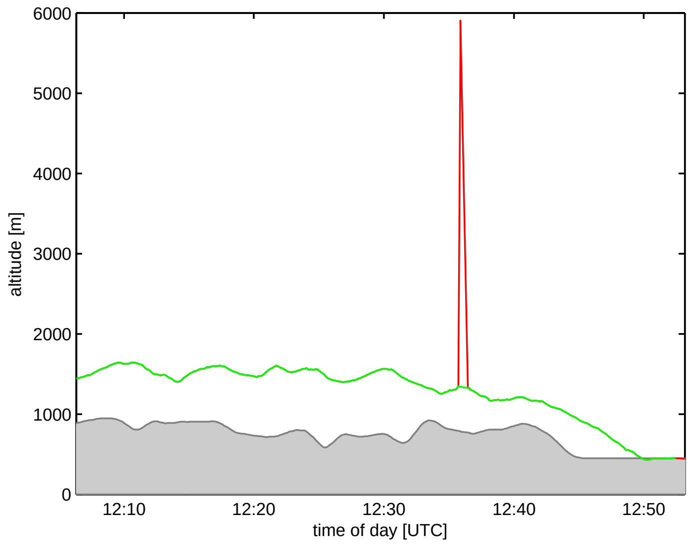

Figure 3.3: A sample flight plotted altitude versus flight time with an obvious spike in altitude in the middle of a flight. Green is the corrected flight path, red the spike in altitude and grey shows the elevation under the path of flight.

Such errors are determined according to speed. Paragliders have a very limited speed window. Depending on the model, used acceleration and weight of the pilot the speed window ranges from 30 up to 60 km/h in calm air. Because the GPS only covers the speed over ground, the relative speed might sink to zero or with tailwind it can sometimes rise over 100 km/h. Other fixed wing hanggliders fly even faster. Spikes on the other side attract attention with much higher speeds between two fixpoints. Often only an individual fixpoint, sometimes a series of multiple following fixpoints, is affected and the problem is

solved by deleting them.
To detect altitude errors one can proceed accordingly. The mean climb rate for paragliders in a thermal is 1.3 m/s in the observed dataset. Variance is low but in special cases climb rate might rise over 6 m/s for a short duration. However climb rates above 20 m/s are sure to be outliers (examples in figures 3.3 and 3.4).
Normally the device is started before launch and is shut down after landing. If the pilot does not crop the flight manually during import, it contains useless information at the beginning and the end. Before launch and after landing are the periods where most of the errors take place. Directly after boot up various errors might occur. Some devices determine a very inaccurate position if they have few satellites and do not mark this by the validity byte. Others more advanced devices slowly calibrate the barometric height automatically or the pilot does this job by hand. Similar problems occur after landing. For example a cuff to the barometric sensor while packing results in a spike in altitude. Additionally, outliers are not the only reasons why it makes sense to trim the track. We also get the correct launch and landing location, which will be used later for altitude adjustment, as well as correct flight duration.

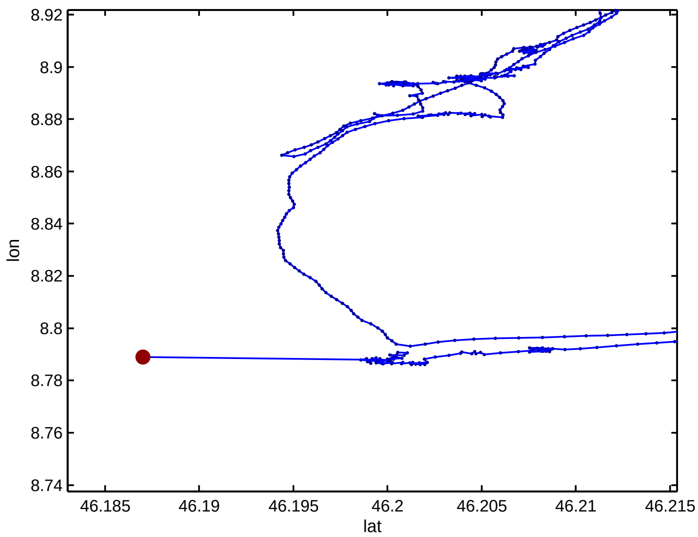

Figure 3.4: Top view of an example flight with a GPS spike in the beginning. Blue is the path of the flight, and the red dot marks errors in position at the beginning.

3.4.3 Altitude Adjustment

Most GPS devices are not limited to GPS altitude but come along with a barometer and sometimes additional acceleration sensors. This is especially the case in variometers with integrated GPS. In this case also smallest changes in altitude are measured. This is crucial for the pilot during flight in order to stay in the thermal since it is difficult to feel a constant climb in free atmosphere. Additionally it helps centering in a thermal, resulting in higher climb rates. The drawback of barometric altitude is, that it needs to be calibrated before launch. If the pilot fails to do so this results in a constant error in altitude, assuming the air pressure remains on a constant level during the flight. Since start and landing are always on the ground, the correct altitude can be computed using a digital elevation model (DEM). About 20% of all flights use an altitude which significantly differs compared to the DEM. So this error can be reduced by fitting the start/landing altitude to the model also shown in an example in Figure 3.5.

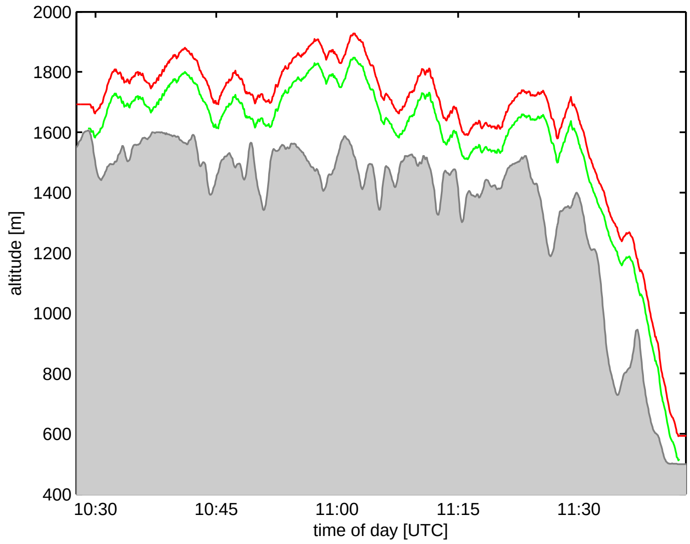

Figure 3.5: Altitude correction of a sample flight. It shows altitude versus flight time. The red curve is the original one and the green one is pinned to the altitude of the launch spot.

However some pilots forget to boot their GPS device before launch or just start it when the conditions in air seems to be good. On the other hand, it might happen that a GPS recorder runs out of battery and therefore stops tracking during flight. Such errors are often hard to detect. Elevation correction for launch and landing spot are therefore compared in order to determine a good reference point to the terrain. Because the used DEM (as most others, too) is more accurate in flat regions [17], the landing spot is generally better suited.
The idea comes up to just pin the whole flight to the lowest point over ground. This idea is especially bad if the flight is near steep rock faces where the DEM is very inaccurate. A lot of flights contain some parts where they are very close to a steep surface since the best updrafts often can be expected there. By just using the lowest point over ground of the whole flight, the error might rise up to 100 m (the highest possible error of the used DEM). This effect might even increase if the GPS position is by fault some meters nearer to the rock face. On the other hand this means, according to the DEM, that valid tracks might go below the earth surface for some time. Fixpoints encountered considerably lower than the maximum expected error in altitude indicate an unknown or at least uncorrectable error. This might happen when logging start and end was during flight or in cases where the pressure of the atmosphere changed quickly. Such errors can not be corrected further and the track needs to be sorted out.

3.5 Identification of Thermals

A corrected track can be analyzed for thermals. After applying the described smoothing, a lot of small turbulences are already filtered. The general approach is now to consider every climbing phase as a thermal and then remove, crop and connect until one ends up with valid thermals. Regions with uplift are easy to detect by just looking at the change

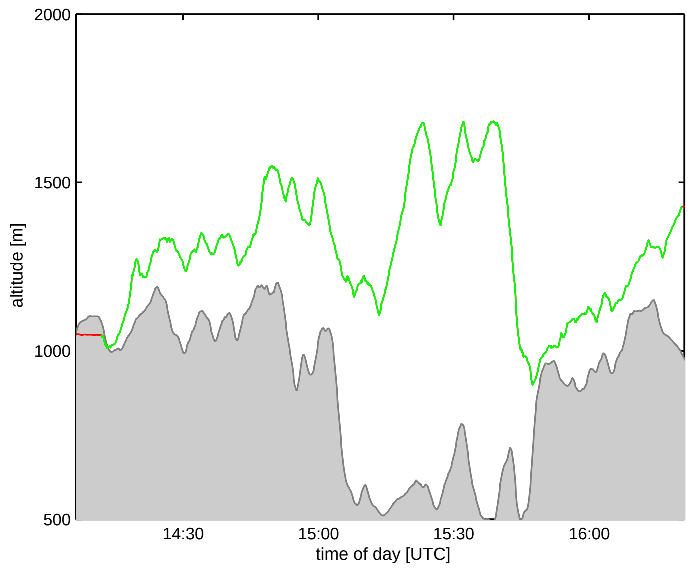

Figure 3.6: The red part before launch is cropped. It contained erroneous GPS positions because of the initialization phase results in a faulty altitude. Logging of the flight stopped somewhen before the landing.

in altitude. This climb rate must be higher than a defined minimum value. For example a sink rate of only 0.5 m/s of the paraglider indicates rising air, since the minimal sink rate of an average glider is above 1 m/s. As described in Section 2.3 these soft updrafts are not of interest and therefore a minimal climb rate of >0 m/s was used, where the pilot can actually gain height.
In a first step too short-term uplifts (less than 30seconds) are removed in order to get rid of the remaining small turbulences and little thermal bubbles.

3.5.1 Trimming Thermals

When entering a big thermal, pilots do not turn immediately but hold the direction until reaching the center with the strongest and most stable uplifts. This entry phase often involves turbulences and often they need some time to discover the center. While leaving the thermal, pilots navigate into the direction of the next sub-ordinate target without loosing the ascending air current immediately. The most extreme case occures when pilots climb up to a cumuli. Since they do not want to get sucked into the cloud, they leave the center of the thermal early to reach the clouds base at its border in the ideal case. A sample is illustrated at Figure 3.7. All these effects are bad in order to identify the center of the thermal and are bad for the linearization as will be shown later.
Multiple algorithms were tested in order to identify these parts of ascending air. All of them rely on a high logging frequency since one has to crop parts which last for about 10 to 30 seconds only.
A first attempt was done using the paragliders relative speed. Relative speed in this context means the horizontal speed compared to well choosen fixpoint. The fixpoint can be the position of the last thermal or just any point on the gliding phase. Another option is to just take the position a longer time ago. The basic idea is that the highest speeds relative to the whole track are reached during gliding phases including entering and leaving of a

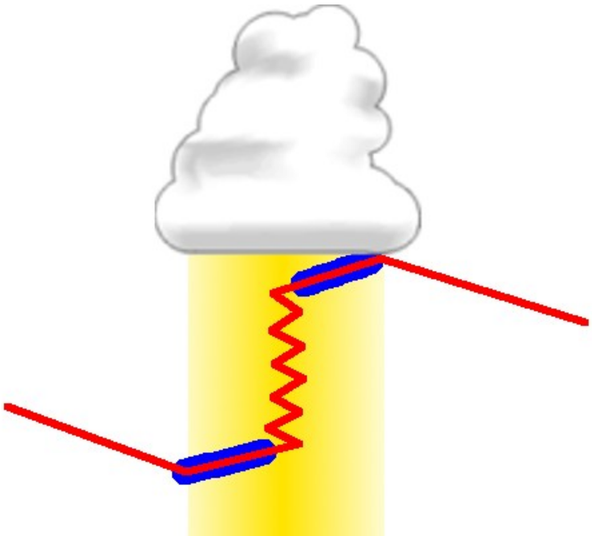

Figure 3.7: Sideview of an ideal big thermal. Red is the path of the flight entering the thermal from the left. Entry and exit phases are pointed out in blue.

thermal. The gliding speed relative to the air remains more or less the same. The pilot can slightly influence this by breaking in order to minimize sink speed or accelerating in order to optimize glide angle against the wind. But the horizontal speed of these extremes differs maximally by a factor of two. Considering a vertical thermal, the relative speed sinks towards zero while circling in the thermal.
In order to detect thermals in a cross country flight, relative speed performs nearly as well as using climb rates. However the transition between gliding and thermaling is too fuzzy and does most of the time not help cropping entry and exit as well especially if using a fixpoint a fixed time ago. But even using relative speed compared to a good fixpoint leads to problems like a the size of the cutoff value to use. A good cutoff value depends on minimum glider speed, thermaling style of the pilot and the weather conditions. This turned out to be a very difficult and crucial task.
A more intuitive way to detect entry and exit phase is to detect cycling itself. A single, flat circle is about 30 seconds long so the logging interval must be shorter in order to detect cycling. However it already turned out to be usable if logged with steps of 10 seconds even though cycling appears more like a zigzag line. While cycling, turn rate between three following fixpoints have a high variance but it remains simple to differentiate between gliding phases and cycling as illustrated on an example in Figure 3.9. Additionally the transition is very sharp providing good properties to detect and crop the entry and exit phase.
Figure 3.8 shows an example in 3D. Parts of the flight colored in dark blue are areas where the pilot lost height. All other parts (including light blue) are interpreted as part of a thermal, since the pilot gained at least slightly in height. However, by looking at this figure, it is obvious that the light blue parts should not be counted as part of a thermal. These parts are detected and removed by analyzing cycling behavior.

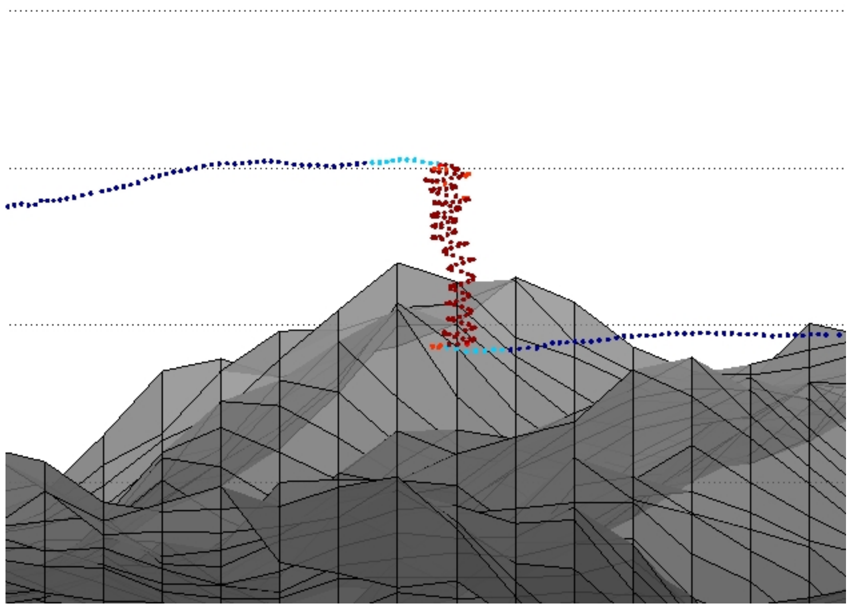

Figure 3.8: Light blue parts are trimmed because no cycling took place. They are longer interpreted as part of a thermal.

3.5.2 Linking Thermals

Sometimes it happens that the pilot looses a thermal by accident. He probably enters the turbulent sinking air beside the thermal and tries to find the uplift again. In other cases the pilot willingly exits a stable thermal and enters the same thermal again later. A third case is a very instable thermal with many bubbles resulting in short strong climbings followed by short sink rates. Till now the algorithm detects each of the climbing parts as a single thermal, but actually each of the climb areas belong to the same thermal. In the extreme case a pilot just enters the same thermal again and again. Gladly this does not happen too often and most of the pilots want to make distance as described in Chapter 2.3. However, if one would not consider multiple climb areas of one flight in one location as one thermal, two problems occur: The well known thermals near to the popular launch pads would be even more overrated as they already are. Secondly it is difficult to detect the trigger point of a small thermal. The inaccurate detection of the origin would result in blurry maps. Two following uplifts which are very near to each other therefore need to be merged into one. The resulting thermal contains more trackpoints and the corresponding trigger point can be detected more accurate.
Two uplifts are considered to belong to the same thermal if the minimum distance of two fixpoints falls below a given threshold. It should not happen that thermals with different trigger points are merged into one. There exists theories about the distance of thermals in function of base height in flatlands. This does not apply for areas with dominant surface. Therefore a safe bet was used. The minimum distance is chosen to be the maximum distance of two track points on an average flight. Considering a 10 seconds interval and a flight speed of 40 km/h, this leads to approximately 120 meters.
Figure 3.10 shows a case where the pilot willingly left a thermal and reentered it again later on. This possibly happened because he did not find the next thermal where he expected it or, likely in this case, the pilot just wanted to maximize xc-points he gets for a FAI triangle.

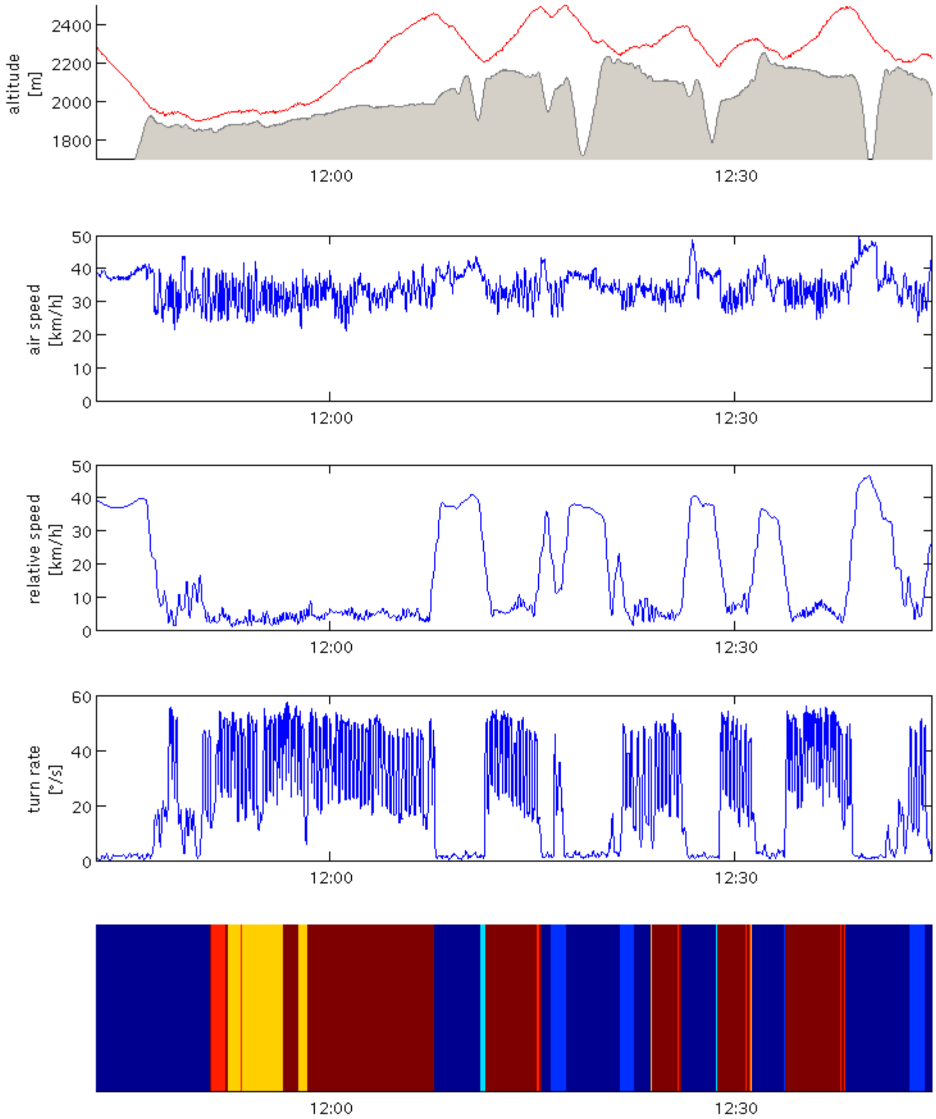

Figure 3.9: A part of an example flight showing altitude profile, air speed, relative speed compared to the position a minute ago and turning rate. The colormap azimuthin the lowest plot indicates thermal type: dark red are good thermals, whereas all blue color types indicate no thermals. Light blue is trimmed because no cycling took place. Parts linking between thermals are colored yellow. Outliers are orange.

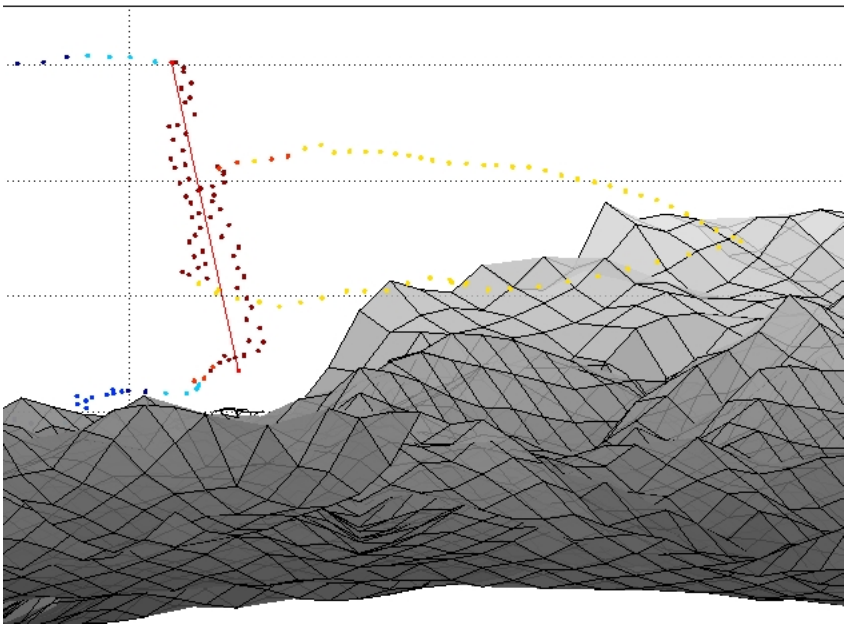

Figure 3.10: Fixpoints of a flight: The pilot entered the thermal from the lower left of the figure, climbing up 3/4 (dark red). Then the thermal was left just to reenter it again later (yellow). Then the pilot climbs the same thermal again and leaves. Dark red parts are interpreted as a single thermal. The dark red line shows its linerarization.

3.5.3 Linearization

At this point the thermaling regions of a flight are well defined. However thermals are not yet in the shape which allows further processing. In order to guess the origin of a thermal, the actual shape needs to be guessed. This is based on the fixpoints in the thermaling regions.

When detached from the ground, an air packet has a horizontal and a vertical momentum. The vertical component can be diffuse and is influenced by various atmospheric parameters (see listing in Appendix A.2). It might vary within different altitudes and it is difficult to measure on basis of the track. Theoretically it should be possible to calculate the climb rate of the air inside a thermal out of the paragliders climb rate plus its sink rate. In practice however this is distracted by bubbles, uneven circles and alike.

The horizontal component however is mainly influenced by the local winds. It is known that in flat areas, wind strength grows logarithmically with height above ground (see also Section 2.1). This is however of little use if guessing the shape of a thermal. First of all most thermals are found in mountainous regions where wind conditions are much more complicated. Secondly, as mentioned before, the vertical component is not the same on every height. It is rather natural that thermal strength increases with increasing height. Finally even if the logarithmic approach holds, thermals are usually flown in regions of fifty up to several thousand meters above ground. In these altitudes the logarithmic approach can be approximated linearly.

Least Square Error (LSE)

The standard approach to find a linear fitting curve in space can be found by minimizing total least square errors. A linear linear fitting can efficiently be calculated by use of the singular-value decomposition.

$$\begin{aligned} x_0 &= mean(x_i) && (3.1) \\ [U, \Sigma, V^*] &= svd(x_i - x_0) && (3.2) \\ a &= V^*\left(:, max(diag(\Sigma))\right) && (3.3) \end{aligned}$$

x_i are all fixpoints in a thermal thus x_0 is its centroid. In a next step the singular value decomposition (SVD) is applied to the difference of fixpoints to the centroid. In a final step, the largest singular value in Σ is found and the corresponding right singular vector of V^* is extracted.

$$x_l = x_0 + l * a \tag{3.4}$$

The centroid x_0 and the vector a describe a line l with least square errors in therms of distance from each fixpoint to the fitting line.
Under ideal conditions, meaning nearly linear thermals, linearization performed well. In most other cases in practice, however, LSE turned out to be a bad choice. This is mainly because few outliers have a huge impact on the linearization. Many outlayers are already filtered before the linearization step but not all of them can be eliminated. Additionally there are other completely normal cases that are badly linearized if justed by eye, for example if a thermal is slightly bended.

Multi Centroid

A much simpler approach turned out to be more reliable. By calculating a out of the centroids in the upper and lower part of a thermal, a much more robust linearization vector could be found. It relies on the fact that thermals are mainly vertical constructs.

$$a = mean(x_{upper}) - mean(x_{lower}) \tag{3.5}$$

A bending of a thermal, for example caused by higher winds in the upper parts of a thermal, is not overweighted by this approach. On an ideal perpendicular thermal this approach performs as well as LSE and returns almost an identical result.
The question remains how to set the boundary for upper and lower part. By lowering the bound between upper and lower part, the entry of the thermal gains more weight. If one defines the lower part as the lowest point up to 3/4 vertical altitude and the upper part as 1/4 up to the exit point out of the thermal, the central part is mainly weighted. In most of the cases it does not matter where exactly the bound is set since similar results are achieved. The threshold was therefore set in the middle between lowest and highest point of the thermal.
By this procedure every thermal can be reduced to two points in three dimensions. Together the two points span the vector a described above, crossing the centroid. The height of the lower point p_1 is set to the height of the lowest fixpoint. Analogous the higher point p_2 is adjusted. Beside the position, the entry time t_0 is an important parameter as well. Further interesting might be the climb duration, average climb rate or wind direction (azimuth). One can even compute an average and theoretical wind strength out of this.

3.5.4 Outliers

In the end some thermals, which do not make sense, need to be filtered.
Entry time will play an important role later on, but it was never checked for correctness yet. The date of the track is corrected while reading the raw data file as described in Section 3.3.2. If the actual time is correct, is hard to determine. However some obvious errors are detectable. Sometimes the time was reseted to 00:00 UTC shortly before launch. In other cases the time shift is bigger. It is generally possibly to go flying during night, but in cases where thermals were found before sunrise or after sunset the whole flight does look suspicious and was removed therefore. Even an hour after sunrise thermals are an indicator for a faulty recorder time.

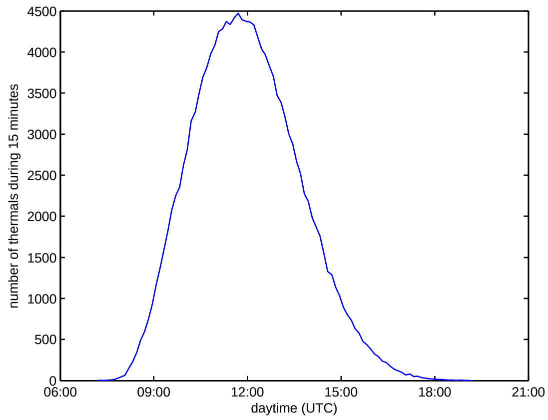

Figure 3.11: Number of detected thermals in a 15 min window over the day.

Figure 3.11 shows when thermals are found in fuction of time of day. Earliest thermals are found around 8:00 UTC and the peak is before 12:00 UTC. In this plot all seasons are just mixed together to give a brief overview. Thermals during night are already filtered out.
Another rare but expected error was soaring mistakenly interpreted as thermal. As mentioned in Section 2.3 the focus is on thermals. Dynamic updrafts needed to be filtered out since they would lead to strange thermal triggers (see Section 3.6).
Some soaring is recognized if there is never a turn during the uplift phase. In very strong thermals it is also not needed to take a turn sometimes. Nevertheless also in case it was actually a thermal, it is hardly possible to determine the correct origin of such a thermal.
Another good indicator for a strange "thermal" is, if the elevation over the horizon is too small. In calm wind conditions, elevation is expected to be near to 90°. Mean elevation angle is slightly lower than 45°, but thermals below 10° are filtered out.
This is worth another note. Since, by a pilots feeling, 45° and below is already an unexpected and low angle to the horizon. In practice and in theory however such angles are to be expected. For example given a thermal of about 2.2 m/s updraft (which means the pilots vario will show climbing of about 1 m/s) and equally strong winds of 2.2 m/s (only about 8 km/h) will already result in an angle of 45°, if bending is assumed to be directly affected by the wind. Also mentionable is, that wind strengths of about 8 km/h and more far away from the terrain is very calm. It is to assume that the pilots feeling of height versus shifting is often misleading.

3.6 Thermal Triggers

As described in Section 3.5.3, the position of every thermal is reduced to two points. Out of these two points the origin of a thermal needs to be found. In a simple theory, the thermal trigger can be found by crossing the extension of the thermal linearization with the ground. But in most cases this is a very bad idea.

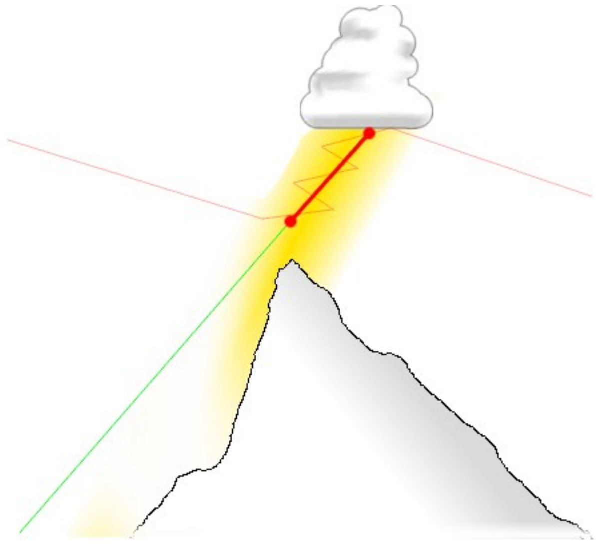

Figure 3.12: Illustration of problem arising by just crossing the linear extension with the ground. Thick and red is the thermal linearization. Light green the linear extension. Crossing with the DEM would be somewhere down in the valley.

Figure 3.12 illustrates the main problem. A simple linear extension often misses a sharp hilltop or cliff marginally where the thermal trigger is assumed to be found. However the real cross section is found somewhere in the valley far away from the thermal.
Generally the origin is assumed to be at least near to the linear extension. The unsureness grows with increasing distance from the lower thermal point p_1. Additionally, according to wind theory, the thermal bends to the ground the last few meters. This had not to be taken into account for linearization of the thermal described in Section 3.5.3. However it turned out to have an impact near to the ground.
Testpoints are chosen on the linear extension of the thermal. Next, the height over terrain for each of these testpoints is determined according to the DEM. The first testpoint is chosen to be the lowest point of the thermal. It is actually not uncommon for this point to lay below earth surface because of DEM inaccuracy near to steep surfaces and the way thermal linearization was done. Horizontal distance between testpoints is defined to be about the size of the resolution of the DEM.
Elevation of all testpoints of all thermals can be calculated in a single query accumulating a huge set of elevation points. The distance from the testpoint to the ground (AGL) is calculated. In the trivial case of just crossing with the earth surface, AGL needs to be less or equal to zero. An easy solution to take also the bending into account is to add a constant to the threshold. For example, assuming the lowest 50 m have a measurable effect one could set the threshold to that height. In this case the thermal trigger point is set to an elevation point (on earths surface) if AGL is below that threshold.
Additionally, the unsureness has to be considered. For example a nearly perpendicular

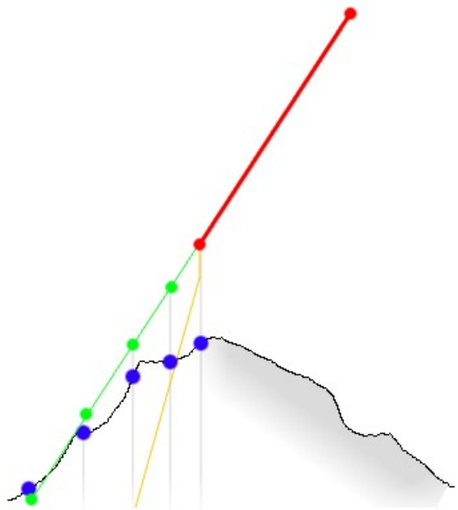

Figure 3.13: Schema of finding a thermal trigger point. Red is the linearized thermal and light green its extension. Green dots mark testpoints. Blue points are the elevation of the DEM below the green testpoint. The AGL threshold is denoted in orange. In this figure the second point from the right on the earth surface (blue) would be taken as a reasonable trigger point.

thermal with a height of 1000 m and with a distance of only about 50 m to the ground, can be precisely allocated to a trigger point. However, an origin for a thermal of about 100 m and higher distance to the ground is not easy to assign. An additional parameter had to be introduced, increasing with distance from the thermal. This distance factor can be chosen higher for short thermals (meaning high uncertainness).
The best option for a trigger point is considered to fulfill the described properties and lies as near as possible to the thermal. All testpoints are checked from far to near and the last match is taken as thermal origin.

$$h_{test} - h_{earth} = AGL \quad \leq \quad c + d * u \tag{3.6}$$

A trigger point must fulfill the stated property of equation 3.6. Shortly summarizing: AGL is the height above ground level of a testpoint. The right hand side describes a cone inside which trigger points are accepted. The constant c allows the thermal to bend to the ground in a greedy manner. And $d * u$ take into account that the thermal might lay different because the pilot did not exactly hit it or the thermal height is very short in order to linearize reliably.

Main Breaklines

In the mountainous parts thermals often emerge from mountain tops and breaklines. Beside the matrix based DEM, *SWISSTOPO* also provides the main breaklines as 3D shapes. This is a very small set of only the most important breaklines.
Similarly to just take AGL into account, also the distance to the nearest main breakline was calculated. Figure 3.14 illustrates the benefit. About 10% of all observed thermals have their origin on a main breakline.

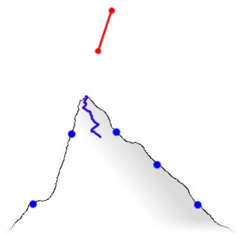

Figure 3.14: A thermal is shown in red. Blue dots mark elevation points of the DEM. Additionally a main breakline (blue) can be used in order to find a reasonable trigger point.

3.7 Final Dataset

The area of investigation is limited to Switzerland. This was decided because density of flights is relatively high, a digital elevation model with good resolution is available and all interesting meteorological parameters are provided for each time instant at every location. Further, limiting the dataset simplified computational effort needed and simplified issues related to coordination transformation in an equidistant system and back.
Flights from the presented community websites were gathered resulting in over 20'000 flights for the period of 2004 to 2009. About 5% of these flights contained uncorrectable errors. All remaining flights were analyzed for thermals as described resulting in about 200'000 updrafts. Trigger points assumed to be valid are found for 94% of these updrafts making the final dataset used to generate the thermal maps described in Chapter 4.
More statistics about the used flights and thermals can be found in Appendix A.1.

4
Thermal Maps

This chapter describes the process of embedding all previously found thermal triggers into maps. The problem of very uneven distribution of flights was solved and seasonal thermal maps generated.

4.1 Cluster Based Approach

In a first attempt, clustering of thermal triggers was tested. As mentioned in Section 2.3, for example DHV-XC focuses on a cluster based approach. The idea is based on flight experience. Pilots know some very stable thermals (Hausbart) one can expect anytime to be at a specific point.

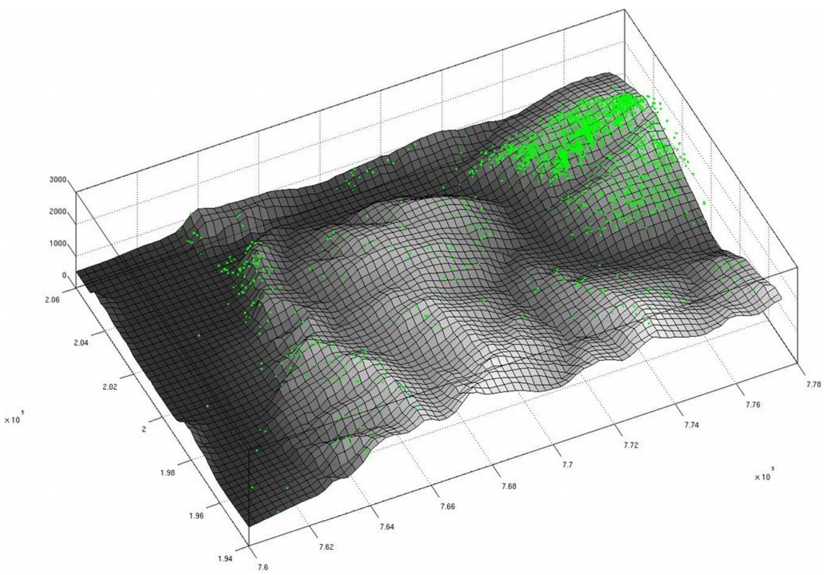

Figure 4.1: Each green point shows a thermal trigger. Not filtered in any way. Scale is in meters (CH1903+ coordinates).

Already by eye (Figure 4.1) it becomes obvious that thermals actually do not cluster. In fact they shape areas. The cluster based approach was retried several times taking into account different filtering options (like weather described in Section 4.2). Sadly it always lead into a dead end and had to be replaced by a raster based approach (see Section 4.3). Since a lot of pilots desired to have thermals as single points, hotspots (Section 4.7) were extracted later on.

4.2 Weather Filtering

First it was assumed that thermals could be filtered by different weather conditions and will build clusters in fuction of the conditions. For this task Regtherm forecast (see Appendix A.3) for the observed time period was used as a reference.
Several weather parameters, such as height of cloud base, wind direction and strength, expected thermal strength, atmospheric pressure and so on were tested if they densify the maps. Especially different dominant wind directions were assumed to give different thermal maps. But it turned out that each tested filtering parameter only dense out thermals equally. The only parameters giving significantly different results were time of day (different sun angle) and time of the year.
Surely overall weather conditions have a huge impact on how one has to fly and where. For example clouds base gives approximately a maximum thermal height but it has no measurable impact on where thermals are found according to the available dataset. The wind parameter of each thermal was already filtered out by defining a trigger point. Thermals with the same origin found under different wind conditions are therefore comparable. Nevertheless it is surprising that positions of thermal origins do not change significantly. A possible explanation might be, that most flights are done under very light wind conditions with good thermal properties and there is nearly no data available showing thermals in strong winds.
But weather conditions define on a given day, the region where pilots fly and which launch spot they use. Adding a theoretical and very good weather filter would not change the location of thermals, but show some regions as thermal active and others as not instead. Looking at all thermals at once, each region shows 'good' thermal conditions. In reality, having good thermal conditions in every part of Switzerland on a given day is rarely the case.
The following list summarizes the gained knowledge about the impact of weather on thermal origins:

- Weather defines the region where pilots perform best (like Tessin, Jura, Wallis, etc.).
- Given such an area, available flights were made under similar weather conditions.
- Time of day and day of year have a measurable impact on the location and density of the thermals.

As a conclusion, thermal maps are generated in function of day- and yeartime and all other weather parameters are neglected. But local weather conditions are the most important parameter for choosing a launch pad which was looked at in Section 6.3.

4.3 Raw Raster Based Thermal Maps

Since thermals turned out to shape areas instead of clusters, a raster based approach is used. This means that the whole area under investigation (Switzerland) is divided into small squares. During this work mostly a raster size of 100×100 m is used.
In a very simple case, each element would just represent the sum of all thermals laying inside its boundaries. In Section 4.2 it was already stated that time of day and year is a good filter property. Therefore several maps are generated. In order to simplify the process, only six different time filters are used. Day of the year is separated into spring and summer/autumn and time of day into morning, noon and evening. During winter, too few data samples are present to generate meaningful maps, even for spring evening only few thermals are available. The separation is done in a way such that the difference between the maps is as significant as possible. According to this, the change-over between spring and summer is near to the beginning of May. The transition is weighted linearly over 40 days. Morning is defined to be before 11:00 UTC, evening after 13:00 UTC and noon in between. Transitions are made fluently over 2 hours. Additionally one could apply linear weighting with respect to time difference. Additionally thermals are weighted according to height. Reasons are that high thermals are more accurate to find a trigger point and they trend to be more stable.
Every thermal is weighted as described above and each pixel just represents the sum of the weights. These maps are further referred as raw thermal maps.
It is possible to generate maps for a very specific time by just taking thermals found near to this time instant. For example every thermal near by 30 days of the day of year and near by 2 hours of the time of day might be similar enough to be taken into account.

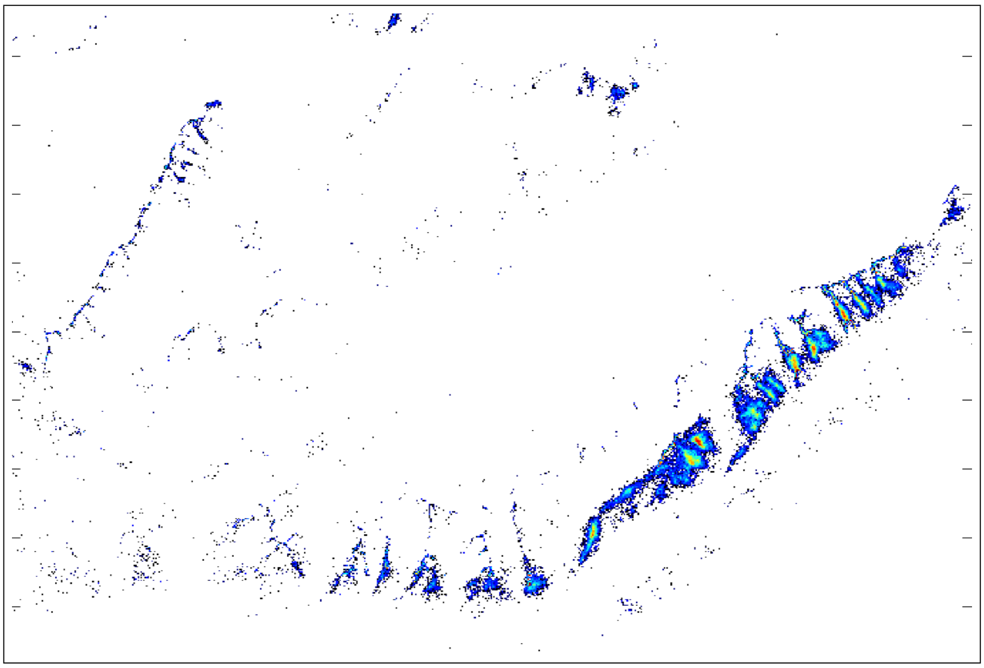

Figure 4.2: Raw thermal map for a summer noon. Color warmth (logarithmic) indicates number of thermals. Goms in the lower right and southern Bern (Kander- & Engstligental) in the upper left corner.

4.4 Knowledge Maps

In Figure 4.2 a raw thermal map is shown. Good thermal regions are already visible (red parts). In the valley of Goms there are more flights per area than in any other part of Switzerland. Because this area has a lot more flights, there are also more thermals found. Choosing the color-range appropriate for Goms, such that good thermal areas are red and bad ones are dark blue or white, means the whole rest of Switzerland appears maximally in a light blue (meaning bad thermal properties). So no matter how the color-range is chosen, in raw thermal maps, ares with a lot of flights are overrated.

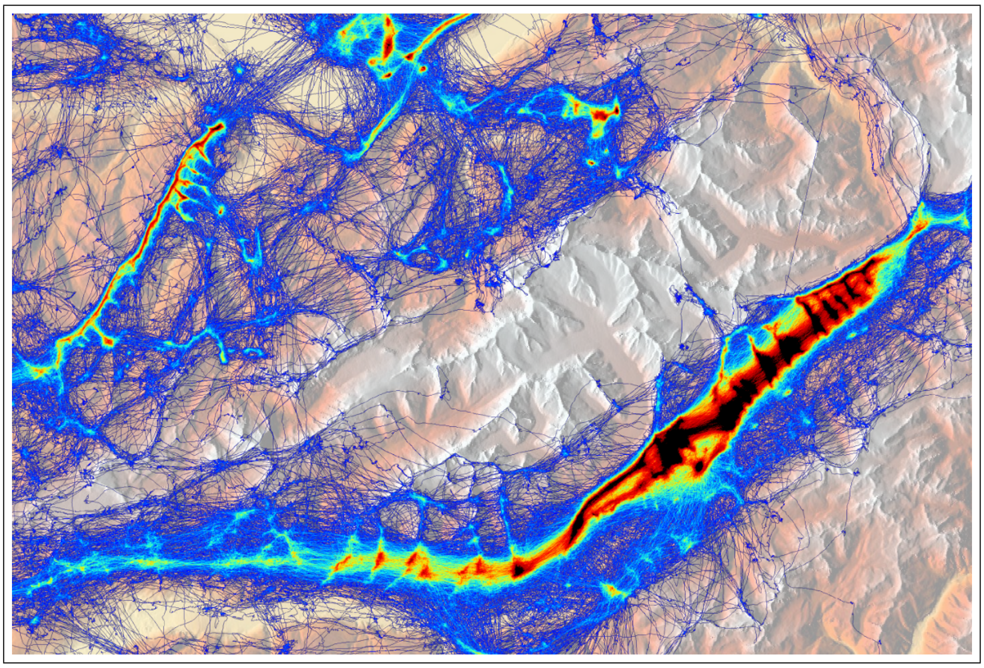

Figure 4.3: Skyways of all seasons showing the valley Goms, a known paragliding highway. The more intense, the more flights went through a given area. Most dense pixels of 25×25 m reach over 1500 flights.

In fact, flights are very unequally distributed. There are the well known routes with thousands of flights and right next to it not a single one can be found. This might mean that there are no thermals at all and therefore the pilots avoid these regions or (more likely) pilots act more on the side of conservatism and stick to well known routes as well as to routes near to civilisation.
The uneven distribution of flights has to be taken into account in order to make maps comparable over the whole area of investigation. Therefore a new map is created showing the knowledge in each of the regions. It is a blurry version of the skyways (which is shown in Figure 4.3). The skyways itself are not good to use directly as knowledge map because the line each flight draws, is too narrow. When looking at a flight from above (in 2D), thermal origins often do not take place directly below the flight track. Most of the time the origin is slightly shifted like described in Section 2.1. Taking simple skyways in order to express knowledge about a region would mean, that there are thermal triggers where no flights are at all. In regions with many flights, this effect is reduced but still has a negative impact.
The actual knowledge map was created by applying a cone filter to a seasonal skymap in

a way that each flight can increase knowledge of a region by a maximum of 1. The cone radius is longer than the raster size. Or expressed in other words: finding a thermal for a pilot is easier than hitting a 25×25 m square placed at random. Flyable thermals are, first of all, bigger and even if the pilot is close to a thermal he might recognize it according to bumpy air and similar effects. Though the thermal detecting horizon was chosen to be much bigger and linearly decreasing the further away from the pilot. Apart from that, the main purpose of the knowledge map is to give answers if there are several thousands of flights in an area or only about ten.

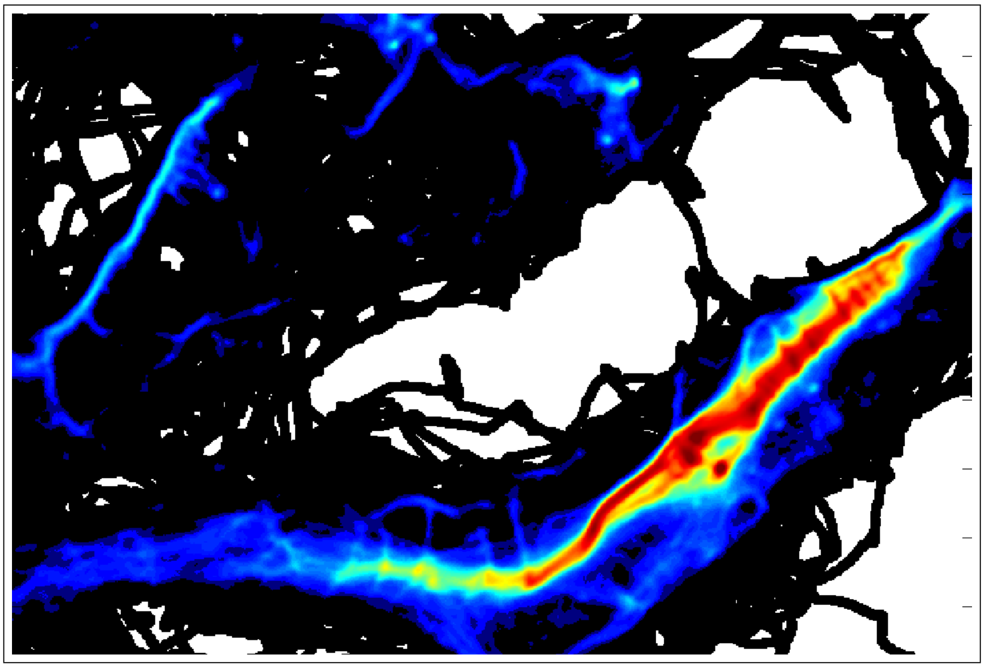

Figure 4.4: Knowledge map for summer noon. Color-map is chosen logarithmically in order to get the whole range into one picture. In black areas, at least one flight was near to 300 meters once. Yellow means around 750 flights are near, dark red goes up to 4500.

4.5 Combination with Knowledge Maps

In a next step, the raw thermal maps and the knowledge maps have to be combined. The goal is to gain a map, allowing comparison of probability to find a good thermal over the whole area under investigation. In a first step, thermals need to be damped according to the knowledge map. In an ideal case, dividing the values in the raw thermal map by the corresponding number of near flights, would result in a map with values ranging from 0 to 1. Where 0 stands for no one flying through that area found a thermal and 1 meaning every single pilot found a thermal at a specific location.
As an example: 200 pilots cross region A and 20 of them find a thermal to be there. Region B is less popular and only 20 pilots fly through but 10 of them find a thermal. Even though there are twice as much thermals found in A, region B seems to be much more reliable.
In practice this does not hold. For example, the worst case is a region with only a single flight and a big shift of the thermal trigger point relative to the flight path. Dividing that single value in the raw thermal map (value 1) by a knowledge value below 1 (because of the

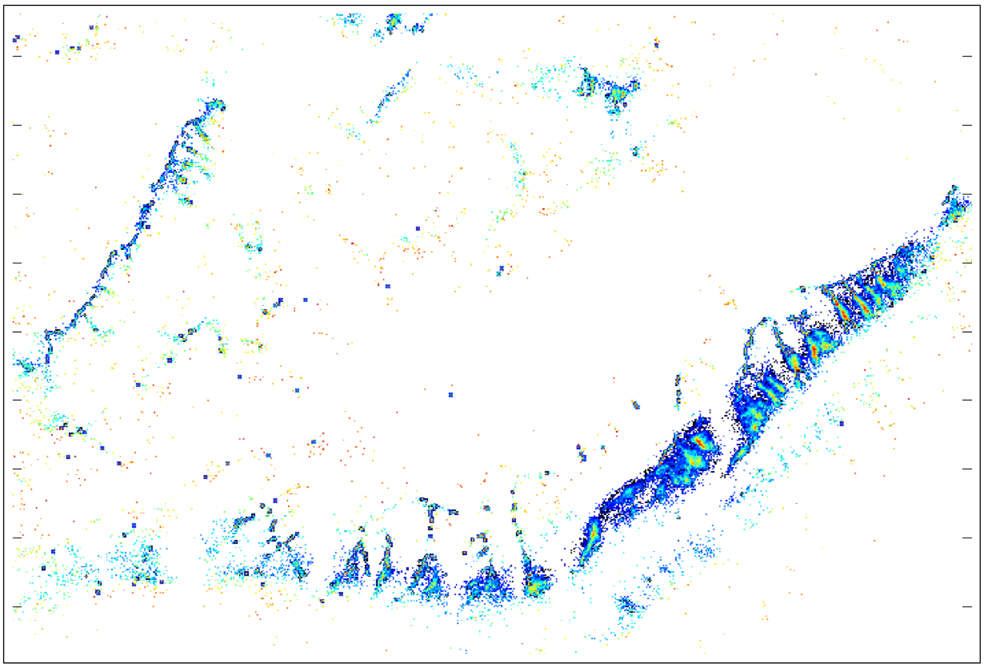

Figure 4.5: Raw thermal map (Figure 4.2) divided by raw knowledge map (Figure 4.4). Red pixels correspond to values around 0.2 and dark blue pixels are at least above zero. Overrated values in regions with few flights (center).

shifting) would result in a thermal probability bigger than 1, which does not make sense. Even by lowering to a probability of 1, this single thermal would be heavily overrated. This effect can be seen in Figure 4.5. In the center (only few thermals and low knowledge) there are single and very high rated pixels (yellow and red dots).
To avoid this effect, the knowledge map was set to a minimum value. One can understand it as the minimum number of flights which are needed for an area to obtain the maximal possible thermal probability. During this work, a minimum flight value of 20 was used, performing well in practice. Theoretically the minimum number of flights should be taken such that it grants a certain statistical significance. It is expected, that actually more than 20 flights would be needed for that.

4.6 Selective Blur

The gained probability maps already show good characteristics to distinguish between thermal active regions and bad ones. However, they have some issues which make them difficult to read. An obvious drawback is, that they contain a lot of noise. In some parts of the map numerous thermals are used, making the maps very accurate. In other parts with fewer knowledge the thermal maps appear more pixelized and noisy. As a side effect, areas with only few and scattered pixels can hardly be seen if used as a map overlay.
Simple linear filtering was tested. Even though this helps to blur out the noise, a lot of accuracy is lost in areas where actually sufficient information is present.

A new filter needed to be developed which can solve the following issues:

- blur ares with noise and low accuracy
- do not blur very accurate areas with high knowledge

In order to achieve this, a non-linear disk-blur is used with blur radius in function of knowledge. Pixels with low knowledge are blurred with a high radius (about 300 m) and pixels in accurate areas are not blurred at all. This filter is further called selective blur. The lowest crowdedness (meaning maximum blur) can be set to zero knowledge. Maximum crowdedness (no blur) is a harder task to determine automatically. Very few raster elements state a probability of approximately 100%, however with setting the maximum to approximately 15% probability (which is the 99,8% percentile of all values) much better maps are achieved.

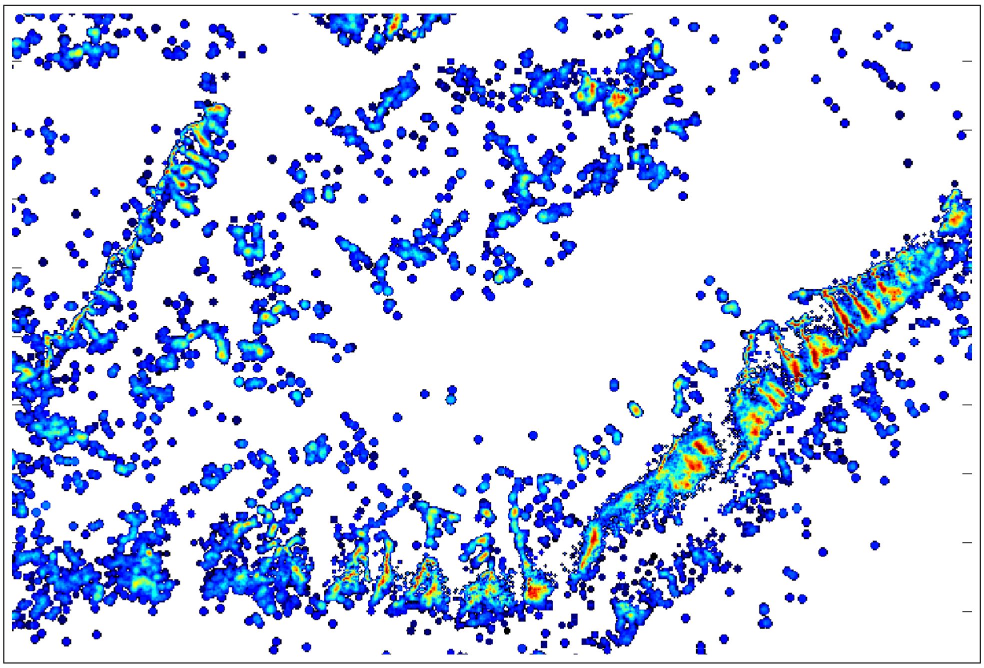

Figure 4.6: Selective blur applied to a probability map (Figure 4.5). Same (logarithmic) color-map as used for the probability map.

Figure 4.6 shows a probability map with selective blur applied. Compared to Figure 4.5, the details in the lower part on the right side (Goms) are still visible. Other areas are now more covering without loosing too much detail. Even in blurry areas this is expected to come closer to reality than some scattered pixels.

4.6.1 Selective Alpha

Because of increased area coverage, thermal maps became more difficult to read if used as a map overlay, because large areas are covered with low thermal probability. To work against this, alpha value was increased for this areas in order to decrease opacity. This also makes the transition between areas without knowledge or very low thermal probability and the adjacent areas with low probability more fluent.

First maps were published in this state. There still existed lots of single thermals (eye-catching blue dots). Especially in the Swiss Plateau (Schweizer Mittelland) with very low flight density but nevertheless, a handful of single thermals, this effect is well visible. The initial intension was to keep these thermals. Even though some scattered big thermal dots do not look realistic, the hope was, that some pilots can still extract some useful information.
Sadly pilots did not understand that these points were just based on low knowledge and did not catch their meaning or even interpreted these as errors. Because of this feedback, also areas with very low knowledge were blurred out in order to not further distract pilots.

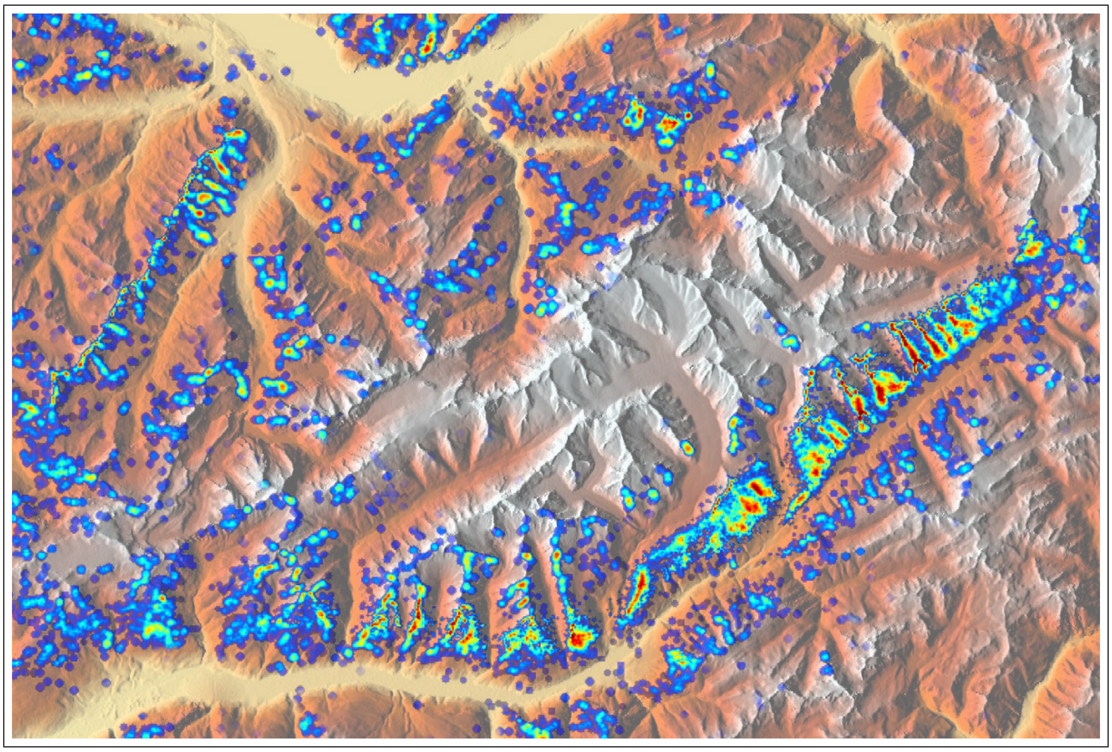

Figure 4.7: Final thermal map inclusive selective alpha in low probability and low knowledge areas. A plain relief layer is used as background.

4.7 Hotspot Extraction

Even though thermal triggers actually shape areas, reducing them to single points (hotspots) would result in many advantages.

- Hotspots can be uploaded easily to every common GPS device, since most of them are only able to show vector graphics and simple dots.
- Hotspots distract less, if shown as an overlay. For example if laid over Google maps.
- Actually representing thermals as points comes closer to most pilots experience because thermals (not the trigger point distribution) have more the form of a tube.
- Many pilots requested this feature.

The gerneral challange is to represent the distribution of thermals as dots such that the dots represent the thermal maps best. Two different algorithms were used.

4.7.1 Greedy

First the maps were filtered by a Gaussian filter. Little spikes are filtered out and the highest value is more likely located at the center of a good thermal area.
A greedy approach was used to extract the best points, meaning the ones with the highest probability. The algorithm works as follows:
First, the highest likeliness of a thermal all over the area of investigation is searched and used as a hotspot. Secondly the area around that hotspot is damped linearly in function of distance the d.

$$v_{new} = v_{old} * max(d_{hv}/r, 1) \tag{4.1}$$

Each raster value v_{old} at least near radius r to the hotspot is damped as shown in equation 4.1. Chosing a small radius places hotspots nearer together. An optimal radius places multiple hotspots on big thermal areas but not too many over the whole area of investigation. For this run a radius of 1 km was used because this is about the minimum distance between the centers of two strong thermal areas.
The algorithm then restarts and the next best hotspot is proceeded. This continues until a minimum probability is reached. The lower this bound, the more hotspots are found per map. Hotspots are extracted from each of the thermal maps and for example for noon a lot more points are found than for evening maps.
If one wants a more even distribution of hotspots over the whole area under investigation an additional much weaker but larger dumping can be applied. The advantage ist that strong thermal regions (like Goms) still only show the most important points and are not just covered by a large number of hotspots.

4.7.2 Facility Location

Greedy brings the problem, that each thermal area is marked at its peak point (mostly the center). No information about the actual shape of the area can be given. Another type of hotspots are extracted using facility placement. The goal is to place hotspots such that wide or strong areas are represented by multiple hotspots, whereas a single hotspot stands for a small or weak area. To find a thermal one has to fly where most hotspots are placed.
Thermal raster elements represent a set of cities T. Hotspots represent the set of facilities F. All facilities have the same constant nonnegative opening cost c_0, representing the minimum thermal probability needed to place a new hotspot. A new facility benefits from all nearby cities by an amount of c_{jf} if the city is nearest to that facility. The metric version of this problem is considered. Each facility has a maximum service range r_{max}, since each thermal can only affect a limited area. The number of facilities to place is unknown and not every city needs to be connected.
The goal is to maximize gain:

$$\sum_{i \in F} \sum_{j \in C} c_{ij} - n_F c_0 \tag{4.2}$$

This problem is known to be NP-hard, however a way was found to split the problem into small pieces suitable for calculating the perfect solution. This is also the optimal facility placement for the whole map.
First areas are determined where the initial cost c_0 can actually be reached if no other facility interferes. Then each of these areas is extended by r_{max} as how far each of the facilities ranges. The problem of facility location can be solved for each closed shape seperately. The thermal maps have the properties that two well defined thermal areas are strictly separated, mostly by a smaller valley.
The number of facilities is initially unknown. The problem is first solved for a single facility (simple), and then each round a new facility is placed. If no better solution can be found by applying a fresh facility, the algorithm quits.

5 Evaluation

Verification is a difficult task since no reliable reference exists. There are other thermal maps, but most based on simpler methods or with another focus. In the end, the most important goal is to improve the flight preparation and analysis for paragliding pilots.
Presented evaluations are based on flights during spring 2010, comparison to other thermal maps and pilot feedback.

5.1 Coverage

First of all, one needs to grasp of the general shape and coverage of the thermal maps in order to understand the rest of the evaluation.
There are numerous areas in Switzerland where no pilot even came close to. In fact, only in about 37% of the area under investigation at least one pilot came close to 300 m. As stated in Section 4.5, to reach a maximum thermal potential, at least 20 flights are needed. This condition is fulfilled in 7% of the area of Switzerland.
Even though the thermal maps are made as opaque as possible, most parts of Switzerland are not covered because no flights or no thermals are present. Figure 5.1 tries to express the coverage of the thermal map in another form. The bottom line is, that only in very few parts of Switzerland good thermal properties could be predicted.

5.2 Evaluation of Spring 2010

Flights of spring 2010 (only till early May) are used as a reference to see how the thermal maps generated with data from 2004-2009 perform.
The new tracks are analyzed by the same algorithm used to generate the thermal maps. All evaluation is done using the representing trigger points. The test set consists of 2700 valid flights including more than 20'000 thermals. These are still too few thermals to generate a new thermal map, so other evaluation methods had to be used.

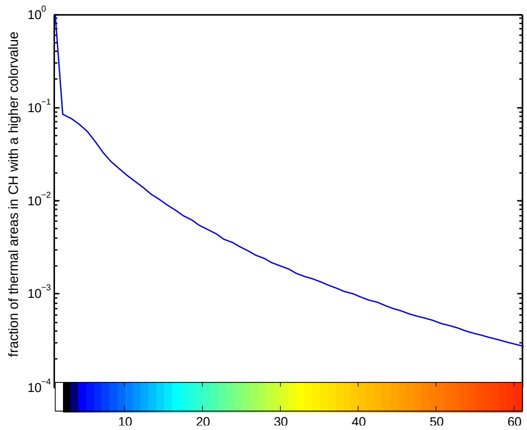

Figure 5.1: Fraction of Switzerland (41'277 km^2) covered with a higher color-value than indicated on the x-axis. Red areas, meaning good thermal properties, cover about 0.02% of CH (10 km^2). 0.6% (250 km^2) are colored in light blue representing usable thermal properties.

Visual Performance

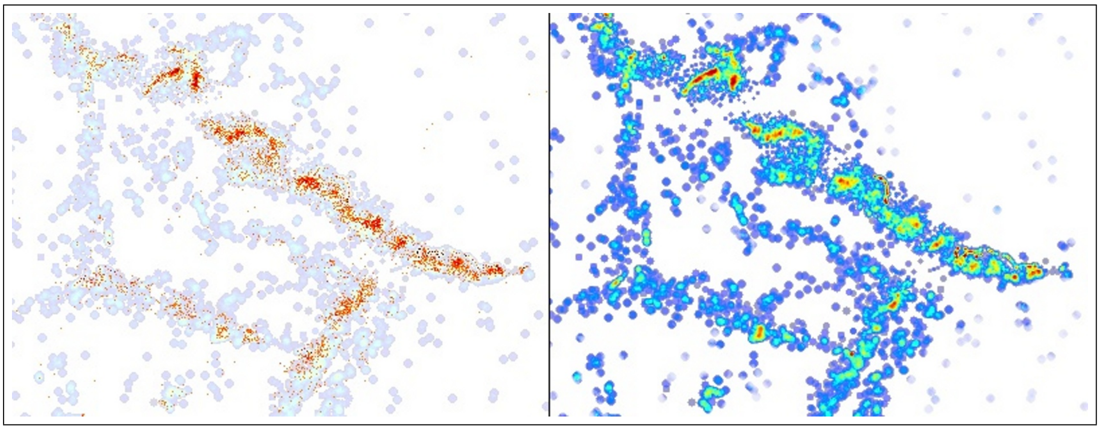

Figure 5.2: On the left hand side, thermal triggers of spring 2010 are shown in shades of red. On the right the corresponding thermal map.

When plotting the freshly found thermals on the old thermal maps (Figure 5.2), the similarities are evident. This is especially the case in well covered areas. All thermal hotspots from the years when the map was created, were also active and at the same place as in the reference year. In blurry areas, where thermal prediction is a lot less accurate, thermals are more often found in unpredicted locations.

Performance and Knowledge

It is hard to express these findings in meaningful numbers. Taking the color-values of the thermal maps at locations where thermal triggers are found in spring 2010, results in a mean color-value of 23. Comparing this to the color-map (for example in Figure 5.1) this represents a value between light blue and green, meaning average thermals. To be more exact, this means in the maps for spring noon a probability of 5% per crossed raster element. It follows, that if a pilot for example checks such an area of 500×500 m (which is

really small), the overall probability of finding an ascending air current is $1-(1-0.05)^{5\times5} = 0.72$.
Recalling the facts of the last chapter, that only a very small part of Switzerland has really good thermal properties, this already indicates good thermal prediction of the maps.

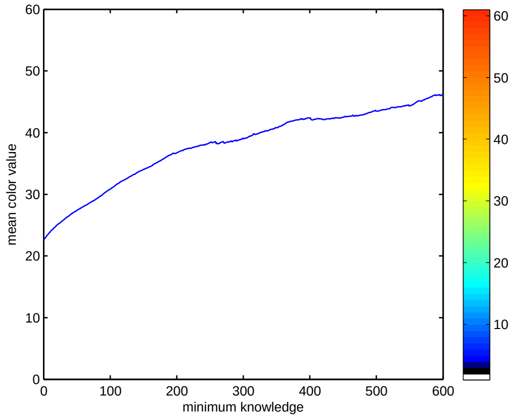

Figure 5.3: On the x-axis the mean color value of the thermal maps of spring if taken at trigger points of 2010 is shown. On the right the corresponding color-values are shown. These color-values are taken in areas with a minimum knowledge. Knowledge is defined as in Section 4.4.

When only investigating a well covered area, where a lot of flights were used to generate the thermal maps, the mean color-value rises. For example only looking at the valley Goms, the mean color-value is 29 (yellow to green, meaning good thermal properties on average). This can be further generalized as indicated in Figure 5.3: The higher the flight coverage (meaning the higher the knowledge value), the better the thermal prediction. Two different conclusions can be drawn, where it is unknown how good they apply.

- Thermal prediction is best where enough data is available. In most parts thermal maps are generated with few information. This would be a good indicator that future maps with even more flights will benefit and give even more precise predictions.

- Most pilots fly where thermals are best and flying conservatively seems to pay off. Again this might be an indicator that good and stable thermal properties are mainly found at few locations reachable by paragliders and the thermal maps show these locations. Or it might be a sign for bad coverage, assuming pilots just stick to the well known routes, even though less known very good spots exist.

More about future maps can be found in Chapter 7.

Weak Spots

As already shown, mainly parts of the maps with low knowledge show loose thermal regions. In spring 2010, paragliding in Jura was slightly better than in the years before. This also means that various flights in Jura mountains traverse areas with low knowledge.
In Figure 5.4, the western part shows thermal maps where knowledge is sufficient. Also thermal prediction was very accurate. On the north-eastern part of the image, thermal

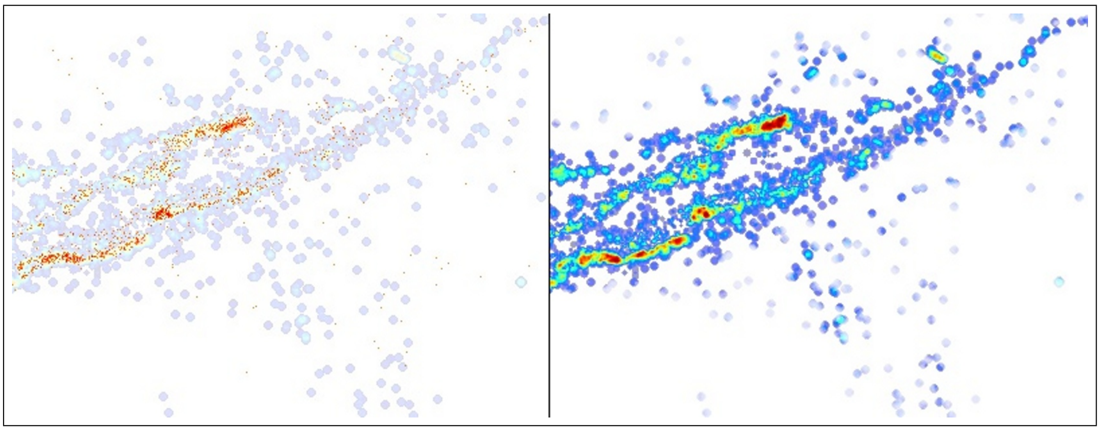

Figure 5.4: The map shows the north-eastern part of Jura and parts of the Mittelland. On the left-hand side, thermal triggers of spring 2010 are shown in shades of red. On the right the corresponding thermal map.

maps would be possible, but only few flights were available. So performance was weak as well. The lower part of the image shows flatlands, where thermal maps are not expected to work at all.
Further thermal spots next to popular launch pads are generally slightly overrated. So not the location is wrong, but the probability is remarkably high. This problem is introduced again by the fact, that mainly the best flights are uploaded. If a pilot does not find the first thermal, the flight is over quickly and likely not to be uploaded at all.

5.3 Comparison to Other Thermal Maps

Actually, the only map similar to the raster based thermal maps is TherMap mentioned in Section 2.4. It is a model based on physical properties, taking into account the DEM and seasonal soil characteristics, but no flight data. This makes it interesting for comparison since the goals of the maps are similar, but the way the maps were built is completely different.

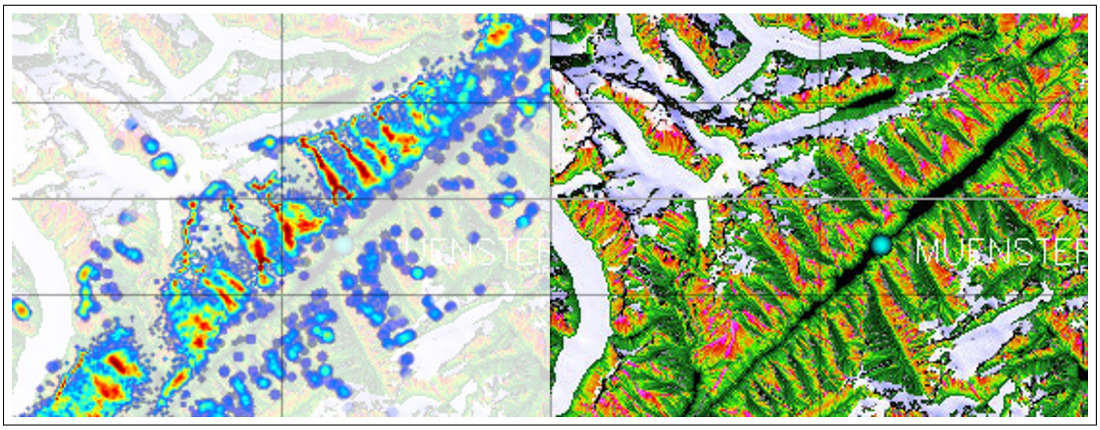

Figure 5.5: Comparison of the thermal maps for a summer noon (left) versus TherMap (right).

A direct comparison of the two maps is shown in Figure 5.5. The thermal map shows the probability to find a usable thermal for paragliders and TherMap shows the thermal pressure representing approximately the climb rate for a glider. This is not exactly the same goal, but in areas where enough information is present for good thermal maps, a comparison is possible.
The thermal prediction on some ridges is practically equal and the shape matches even in details. But there is also a set of small differences. Some of the presented differencies are highlited in Figure 5.6.
TherMap sometimes overestimates thermal potential close to the bottom of the valley (red). This might be due to valley winds, which are not taken into account in the model. In the image section presented, local wind systems play an important part and become quite strong on sunny summer days. This is also the case on the Grimsel pass on the upper right of the figure (orange).
Other differences can be found along some ridges and breaklines (blue), where TherMap predicts no thermals but paragliders actually seem to find quite some. Also generally thermal maps are more concentrated on sharp ridges. This is not surprising, because TherMap shows more the thermal pressure, but the maps created during this work only show the trigger point where the air mass actually detaches from the ground.
Further, thermal maps overrate thermals near very popular launch pads. All flights starting from that launch pad need to catch such a thermal, or else the flight would end quickly and would most likely not be uploaded at all.

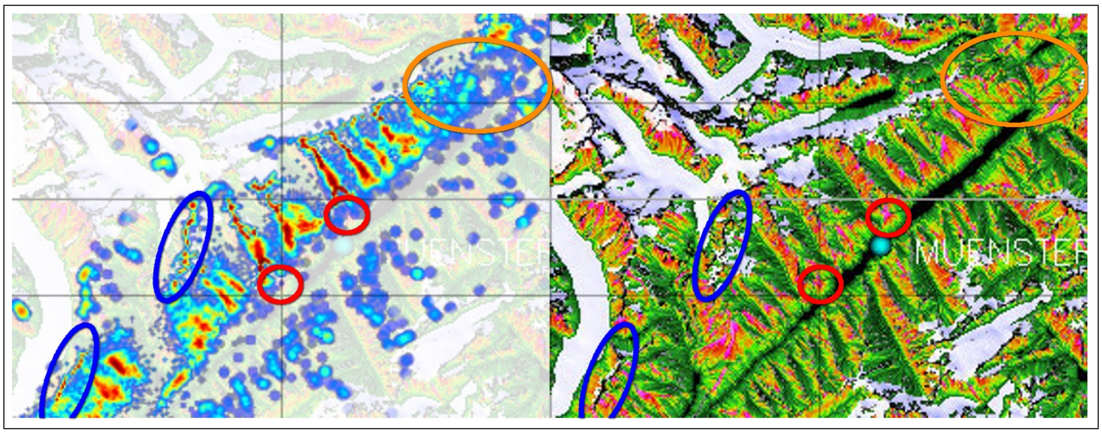

Figure 5.6: The main differences highlighted: The red and orange circles show differences related to valley winds and blue ones depend on the main breaklines.

This comparison was made for a summer noon in the high mountains. For maps during spring and in areas with less dominant terrain, the similarities vanish. Possibly because paragliding pilots, especially in spring, use other kinds of thermals than gliders. Already early in the year, paragliders are able to circle in the strong and small thermals, whereas gliders prefer the more stable and wider thermals during summer.

6 Applications

Several tools facilitating the usage of the thermal maps were implemented. Online maps provide easy access and allow a good and instant overview. GoogleEarth layers allow an experience in 3D. Main hotspots simplify visualization and can be uploaded to all common GPS devices.

6.1 Interpretation of Thermal Maps

This section describes how pilots should use thermal maps and what can be seen on them. It is a short summary of what was described earlier and is the key to use the applications presented later on.

What can be seen

In order to use thermal maps reasonably, pilots first have to understand what can be seen on them and what not.

- Generally the thermal maps are positive probability maps. This means they show areas where the probability is high to find a usable updraft. The maps do not show bad flying areas where down rush is very common and they do not show unknown thermals, where no one flew before.
- Maps are generated only by the use of paragliding flights and are therefore most usable for paragliders and hanggliders. Sometimes (mostly during summer) gliders are able to use the same thermals, but often different tactics are needed.
- Thermal maps show the thermal trigger (the origin of the thermal on the surface). They try to exclude soaring. Thermal turrets are shifted by the wind and merge with other turrets as they rise, which can not be seen directly in the maps.
- Thermal maps perform well in mountainous regions but hardly in flatlands. Few scattered, blue, and blurry dots mean there are thermals found, but they are not likely to be there again.

- Climatic properties are always assumed to be good in a region (in a sense of favoring thermals).

6.2 Online Maps

To be used in online maps, the thermal maps images were cut and scaled into tiles of equal size. GDAL2Tiles (distributed together with the GDAL library[1]) is used to convert the raster file along with georeference into a directory structure of small tiles. It follows the TMS specification[2] describing mapping solutions that use multi-resolution image pyramids.

6.2.1 OpenLayers

OpenLayers is an open source JavaScript library, allowing visualization of geoinformation in a browser. It provides an API for developing client-side applications, independent of the underlying server architecture similar to GoogleMaps or YahooMaps.
An application was developed allowing a quick experience of the thermal maps. Besides commonly expected actions as zooming and panning, it allows switching between all available time segments and visualization of different types. The maps can be examined along with several useful and familiar base layers from GoogleMaps or aside pure elevation data. Furthermore additional features are implemented as described in Sections 6.3 about launch pad prediction and 6.4 about hotspots.

6.2.2 GoogleEarth

Even though 2D maps, as described in the last chapter, allow a quick overview without the need for additional software, the thermal spots are much more memorable in 3D. GoogleEarth is a widely distributed free software showing the virtual globus in 3D. Similar to the 2D maps, these baselayers can be overlaid with thermal maps, too. In contrast to the browser maps, it allows continuous zooming without a lower limit.
Besides the studies of thermals in terrains unknown to a pilot, also the flight analysis is very catchy. There are a great deal of different tools to convert a flight in igc format into a kml file, viewable in GoogleEarth.[3] Figure 6.1 shows an example flight in 3D. Thermals are mostly found at a high point of an area where good thermal properties are predicted.

6.3 Launch Pad Recommendation

In Section 4.2 it was stated, that weather conditions have only a minor impact on the location of the thermal triggers. However, weather conditions have an important effect on where pilots fly. In addition to the thermal maps defining the thermal origins in a region under good thermal conditions, a pilot needs to find out which region is actually good on a given day and which launch pad to use. To aid pilots further, good predictions for launch pads should be made. Because weather filtering according to weather conditions was tested in the beginning, the required weather information was already present.

[1] `http://www.gdal.org/`

[2] `http://wiki.osgeo.org/wiki/Tile_Map_Service_Specification/`, visited May 2010

[3] An easy tool for converting igc to kml is probably directly the import tool: gpsbabel or GiPSy flight manager. More features provides igc2kmz (`http://www.paragliding.delasiava.de/html/igc2kmz_2_2.htm`, visited May 2010).

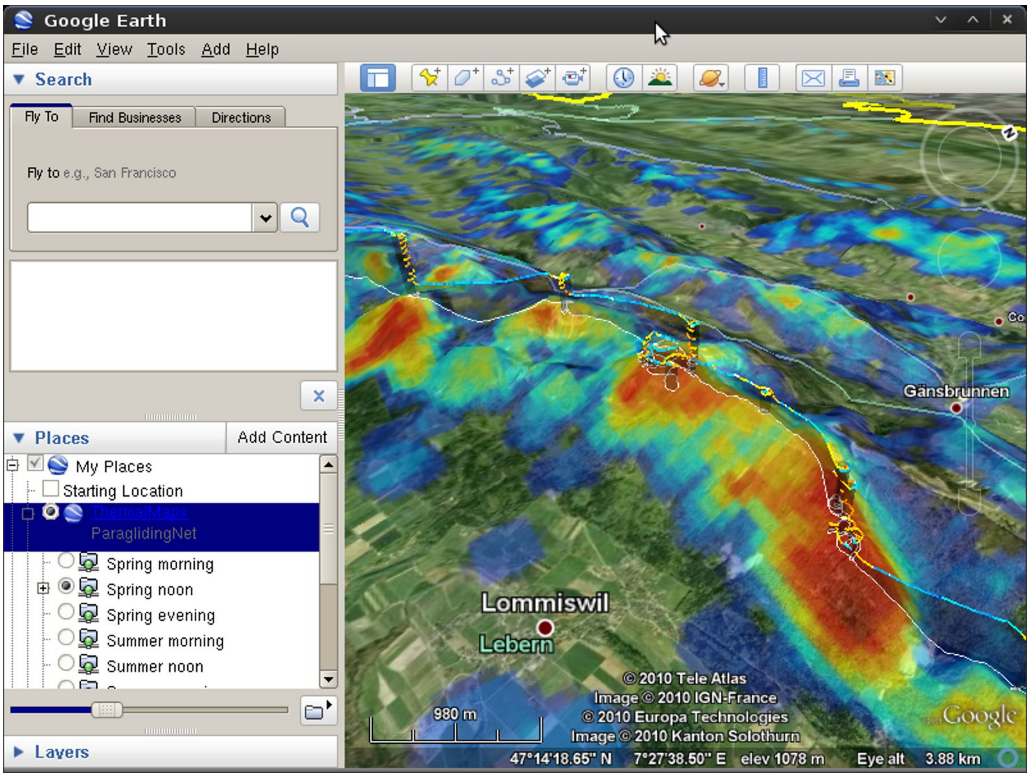

Figure 6.1: Part of a flight in GoogleEarth along with the thermal layer for spring noon made slightly transparent.

Launch Pad Extraction

First of all, the start positions are extracted from the tracklogs. If every flight is cropped according to Section 3.5.1, the first fixpoint of the flight log represents the location of the actual launch. On some mountain tops, there are several actual launch pads. Paragliding pilots chose one of them for launch according to given wind conditions or other parameters like high grass. But all of these launch pads are relatively near to each other and pilots can change to another spot if needed. All launches within a maximum distance d_{max} to any other launch point were assumed to origin from the same launch pad. Multiple launch pads next to each other are taken together and considered as one. The most popular spots contain several thousand launches, but a large number of smaller and unpopular ones hold only about 2 starts each. In this context, popular means a lot of flights from this spot were uploaded. On less popular spots mainly used for short flights, where the pilots did not want to share tracklogs, no information is present. For example, only few flights during winter are available, making it impossible to predict launch pads during winter. It is only possible to predict launch pads for longer, thermal flights. Even though it would be very interesting to recommend something during unusual or non-thermal weather condition.

In order to get further information about a launch pad, like how to get there and information about dangerous cables, links to popular, wiki-based paragliding launch pad webpages were automatically added.

Weather Parameters

The most popular launch spots are further analyzed. The goal is to find similarities between weather parameters and distance flown, given a specific launch pad and given any flight. Wind direction and wind strength are important factors for choosing a launch pad. Further, the clouds base and the time of year showed correlations to certain launch pads. In practice, some hills are known to be good for thermal flight during certain times of the day. However, the majority of the flights started from a morning spot. This is again because mainly the longest flights are uploaded. Each parameter further discussed is taken from the most up-to-date Regtherm at time of launch. For each launch pad, a wind speed window is found based on upper and lower percentiles. Some regions are well protected from the supraregional winds and others need a minimum windspeed. Next, possible wind directions are determined, weighted by windspeed. Some launch pads only have a single launch direction and a small possible wind speed window, wereas others generally allow starts independent of the global wind direction. It is worth mentioning that wind directions for good flights are not necessarily correlated with the orientation of the launch pad itself. Similarly, a window for the usual height of the clouds base and time of year is determined. All these parameters are then weighted by xc-points.
Besides the parameters depending on a certain launch pad, the actual thermal properties of the region is an important factor. These parameters were already shortly discussed in Appendix A.2. The potential cumulative thermal distance of the Regtherm is an easy to use, automatically generated and freely available value representing this.

Performance

The performance of the launch pad recommendation is heavily dependent on the performance of the Regtherm (see also Appendix A.3). The launch pad predications are generally pessimistic, but the results are comprehensible. However, there is no way it could replace a pilots experience (this would also be too dangerous). But it can be used to give further hints about launch pads to consider. With this goal in mind, launch pad recommendation is implemented in the online OpenLayers maps (Section 6.2.1). It should be understood as a proof of concept.
To be statistically more reliant, a much larger set of flights should be used. Especially all small flights would be interesting to distinguish between not flyable, flyable and very good. This topic might become more interesting when a lot more launches are available.

6.4 Hotspots

In Section 4.7 the extraction of hotspots out of the thermal maps and its advantages are described. Some sample applications for hotspots were implemented.

OpenLayers

Hotspots are implemented in the OpenLayers framework. Even though the raster based thermal maps layer represent the actual thermal trigger point distribution much more exact, hotspots are much simpler to visualize and remember. The radius of the hotspots was chosen to be relative to the probability of finding a thermal at exactly that location.

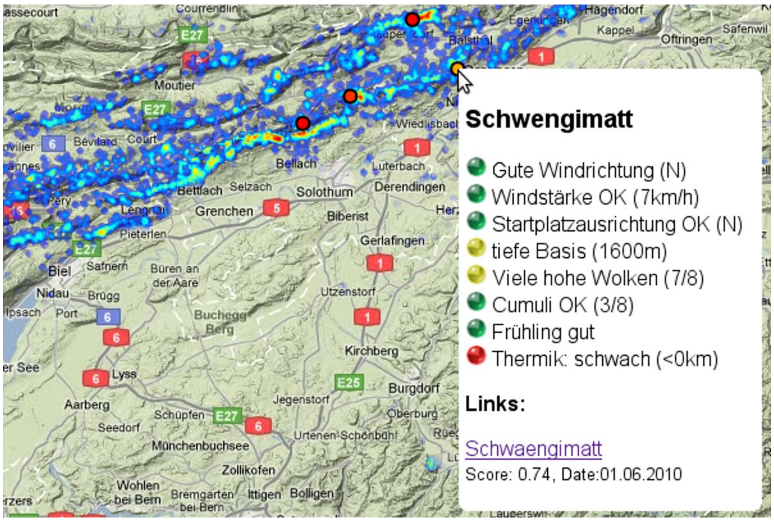

Figure 6.2: Launch pad hints for a rainy day. Several parameters are presented and how they compare to long flights from that launch pad.

GPX

Hotspots are further exported to the GPS eXchange Format. It is an XML based fileformat for storing geodata described by its XML schema[4]. It was developed by TopoGrafix and its license is open and free.
Besides metadata, the format is able to store routes, tracks, and waypoints, whereas only waypoints are needed to store the position of the hotspots. A waypoint is defined by latitude and longitude in decimal degrees on the WGS84 datum. Additionally, the elevation in meters (above sea level) is given even though most simpler gps devices ignore this element. However, elevation information can be used for example for other tasks like automatically determine if a hotspot is in reach given a location and glide ratio. More about further hotspot applications is described in Section 7.3. Each hotspot is given a name starting with a character followed by 2 digits. The character represents the rank of the thermal, where A are the best ones all over Switzerland and D represents more alternative hotspots. The digits stands for the probability of finding a thermal in a circle with 250 m radius centered at the hotspot.

```
<gpx>
  <metadata>...</metadata>
  <wpt lat="47.3234" lon="8.50199">
    <ele>657</ele>
    <name>A98</name>
  </wpt>
  ...
</gpx>
```

Listing 6.1: gpx example

There are various ways to upload a .gpx file to a GPS device. Beside the proprietary software delivered with most devices, the already mentioned GPSBabel does the job.

[4] `http://www.topografix.com/gpx/1/1/`, visited May 2010

Figure 6.3: Thermal hotspots imported as waypoints on a Garmin eTrex Vista©. Hotspots are marked here as big dots.

Having hotspot coordinates on the GPS recorder allows for quick lookup during flights. A popular example device with hotspots is shown in Figure 6.3. Even though studying before flying gives a much better picture than the tiny display, it allows exact targeting for example while overflying a valley. It also might help in case the pilot forgets about some good spots, because he has few knowledge of the area or because he quickly had to change his plans. Obviously, if a pilot has other sources of information like cumulus clouds, circling birds, flying leaves and so on, he might be better off with going for these indicators.

7 Future Work

Reusing flight logs of paraglider or gliders based on a collaborative system is a new topic. It opens a door to a set of new opportunities not only for thermal research. Some approaches on how to further develop the presented thermal maps are presented along with some new ideas.

7.1 Next Generation of Thermal Maps

7.1.1 Optimizing Current Maps

It is expected that thermal maps will benefit from adding more flights (some hints are given in Chapter 5). In some areas with many flights, the maps are not expected to become more accurate, however most areas have poor coverage. Therefore most interesting are future flights in alternative regions and during special times (early and late during the day). The algorithm of creating the maps does not need to be changed since it adapts itself to any flight input. The same applies for the whole correcting routine which will remain usable at least as long as paragliders show similar flight characteristics as nowadays. If glide ratio or speed doubles in the nearer future (not expectable), small adaptations would be needed.

7.1.2 Worldwide Thermal Maps

It is possible to apply the current algorithms to the whole world. Limitations where thermal maps are expected to give good results are discussed in Section 2.2. However practically, one has to deal with several technical limitations. This starts with the used DEM which for example needs to be changed to the free SRTM. In mountainous areas the lower resolution has a big influence on the accuracy of the trigger points and elevation correctness of the flights. For larger maps with the same resolution, memory limitations become a problem soon. The world needs to be split into smaller parts to overcome this. And a lot of computing power is required to deal with the larger flight database.

Generally it is not only possible to generate thermal layers for the whole world, it is also an often requested feature.

7.1.3 Glider Maps

Thermal maps generated similarly should also be possible for gliders. However other effects different from well defined thermal tubes are more important to gain height compared to paragliders (as discussed in Section 2.3). By tuning the algorithms used during this work, thermal maps generated out of glider flight logs should be possible. An expected difficulty is to differ between thermals and other sources for climbing.
Also an interesting topic might be the combination of thermal maps for gliders and paragliders since many glider hotspots are also usable by paragliders if the reach it with enough height.

7.2 Launch Pad Prediction

In Section 6.3 launch pad recommendation is presented. It holds great potential but, from the point of view, more launches are necessary. In fact, it is only needed to know the exact launch time whereas position and the rest of the flights is less important. Most interesting would be to have all flights and not only the best ones. Some pilots do this already to have a complete flight journal, but it is generally frowned upon the community. Other sources of information could also be taken into account like sell statistics of cablecar tickets to pilots. Having at hand all flights frome one launch pad would allow to distinguish between not flyable and flyable conditions. With the current type of flights at least predictions for popular and long thermal flights are possible since many of them are uploaded. In a first step, pilots would already profit from knowing good/flyable wind directions and speed windows.

How to gather more flights?

A lot of pilots nowadays use a GPS recorder but actually only a few upload their flights. It is assumed that most pilots just use it in private to analyze and remember them. Some just do not want to show their flights (particularly the small ones) and others only upload the very best. So the community does not only honor good flights (highscore race) it also prevents some less confident or beginning pilots from uploading small flights.
For thermal maps and similar applications it would be beneficial to have as much raw data as possible. A way to boost uploads might be an anonymous upload function where flights do not show up in highscores but can be used for mapping. Pilots themselves would profit by this voluntary participation from better thermal predictions.

7.3 Next Generation Hotspots

Currently hotspots are static except dependance on season and time of day. Taking a portable device like a PDA or cell phone with a GPS module on a flight, other dynamic applications are possible. For example given a position and glide ratio, hotspots currently in range can be shown.

Also new algorithms to find the best location for a hotspot given the thermal maps need to be found. There are a number of different aproaches to minimize the number of hotspots but still showing all relevant locations.

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A Appendix

A.1 Tracklogs

A.1.1 Weekday

About twice as much flights are done on weekends compared to a work day (Figure A.1). This might tamper the data since flights are not only weather dependant. But as Figure A.2 illustrates, mean xc-points are more or less the same on every day of the week.

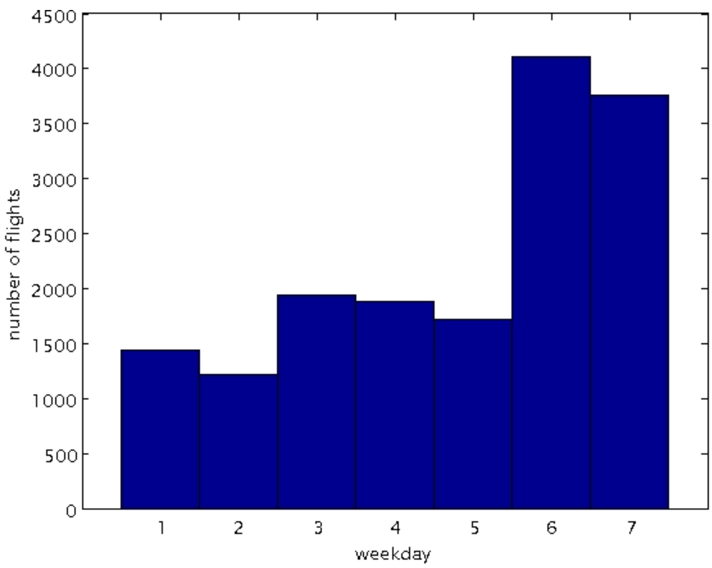

Figure A.1: Number of flights of the used dataset compared to weekdays. Weekdays 6 and 7 represent the weekend.

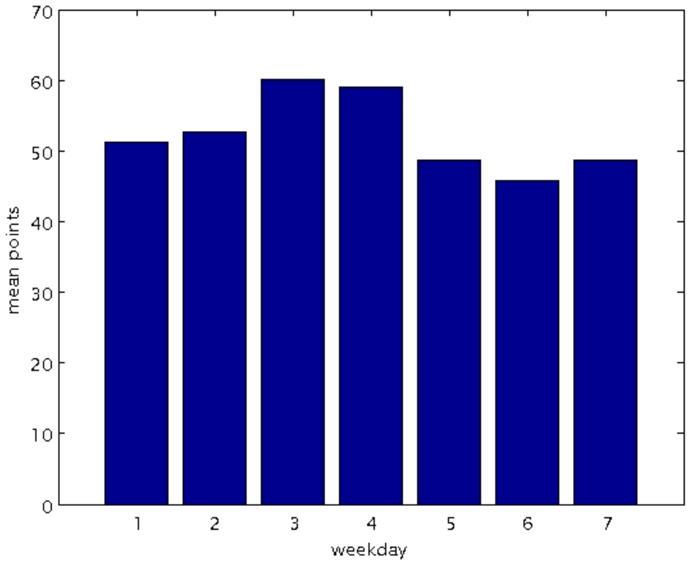

Figure A.2: Mean xc-points of flights on a given weekday (1 represents Monday).

A.1.2 Total Thermal Height

The scatter plot in Figure A.3 scatters the sum of the thermal heights versus the xc-points of that flight. The two values are strongly correlated. Worth mentionable are the flights with many points but no or only small thermal height gain. This can have numerous reasons. For example the thermals were very strong and close together and the pilot had no need to circle at all, or a big part of the flight is done by use of soaring. It is also possible that there was never the need to gain more than the minimum height (50 m) in a thermal. This was the case in the most extreme flights shown.

A.1.3 Regtherm Comparisons

A.2 Weather Conditions Favoring Thermals

Weather conditions favouring the appearance of thermals is not an important part of this work. Sure it is important for pilots, but during this work, most of the time the conditions in every region are assumed to be 'good' for thermals. Even though some important parameters for the area under investigation are listed here for completeness, without further explanation: [18, 10, 8]

- Wind direction
  Wind from the west over north to east generally brings continuously cold air over the warm earth surface, conserving the lability. More important, paragliders requre head wind (or at meast no wind) for launch.

- Wind strength
  Generally the less wind the better the thermal potential. If over 15 to 20 kt in the mixing layer, no more thermals are found exept in specially wind protected regions.

- Gradient
  The temperature gradient of the atmosphere plays an important part and should

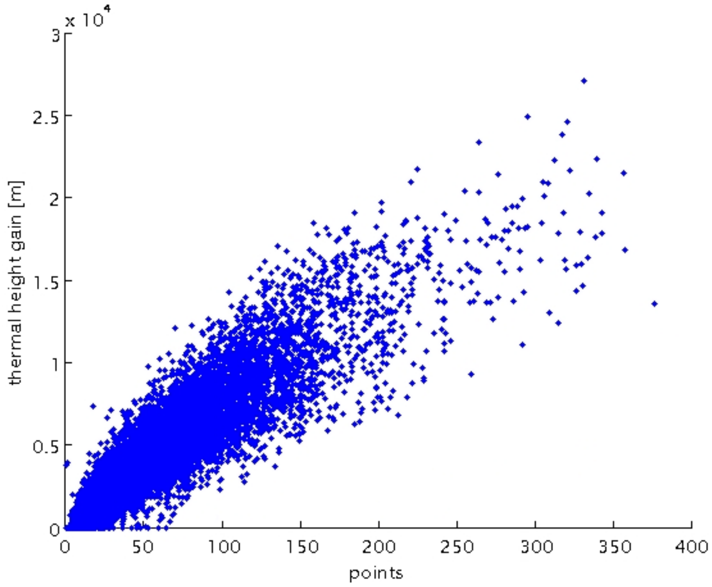

Figure A.3: Total thermal height gain per flight scattered versus points. Thermal height is defined as As mentioned in Section 2.3, for example DHV-XC focuses on a cluster based approach.used during this work.

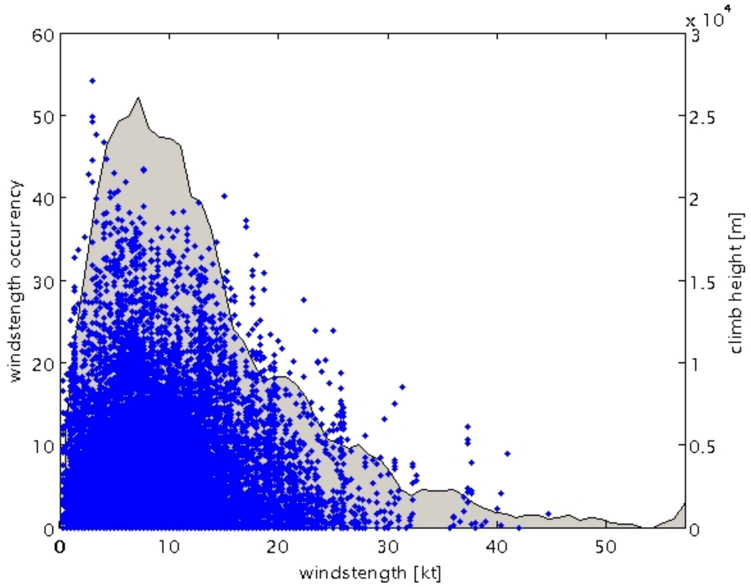

Figure A.4: The blue scattered dots show an average windstrength over the flight compared to the sum of thermal heights (right y-axis). Mean windstengths are taken from the Regtherm at the position of launch and represent the winds in the mixing layer. The gray area represents the mean occurrence of a given windstength over the observed time period (left y-axis).

be between 0.6 and 0.8 grad/100m in the lower parts. Low values represent stable conditions and too high values tend to form bubbly thermals. In higher parts an inversion is prefered minimizing the risk of thunder storms.

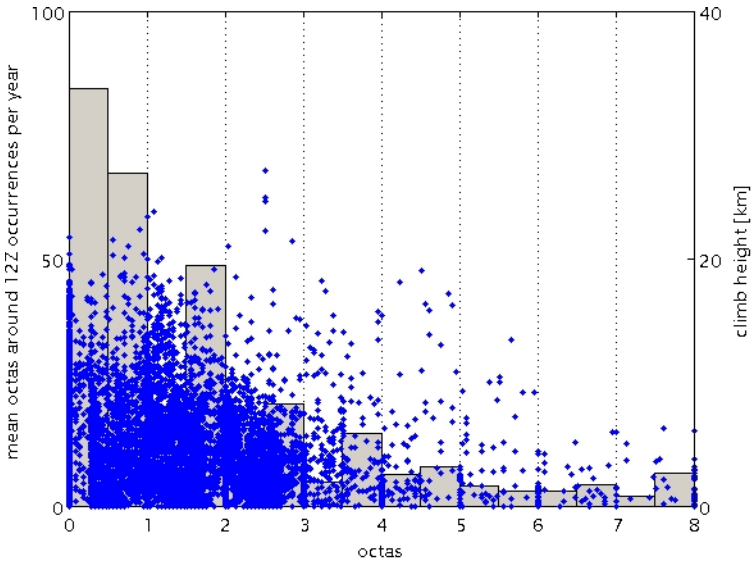

Figure A.5: Each blue dot represents a flight showing mean cumuli (in octas) taken from the Regtherm versus sum of thermal climb (right y-axis). The gray bars show the number of occurrences around 12UTC over a year (left y-axis).

- Spread
  The dew point is the difference between the temperature and dew point temperature at a certain height in the atmosphere. A high spread in the upper part of the athmosphere is desired also minimizing the risk of thunder storms. In the lower parts it should still allow dew adiabatic ascending.

- Bending of isohypses
  Should be anti-cyclonic such that to be in the area of influence of a high pressure area.

- Atmospheric pressure
  If air pressure is high, subsidience dominates (sinking air) dominates. Low pressure in combination with cyclonal activity results in clouding which is also bad for thermal activity. Best is between 1015 and 1023 hPa, however also higher pressure up to 1028 hPa has shown good potential for long cross-country flights in the investigated dataset.

- Pressure change over the day
  The lower the better.

- Foehn
  For paragliders (in contrast to gliders) foehn is a dangerous phenomena because of the turbulent and stong wind on the lee side. A pressure difference of 3 to 4 hPa is a good indicator but also wind plays a role.

- Clouds
  Best is 0/8 to 2/8 cumuli and no high clouds. Prognosis over 3/8 showed to have a bad impact. Hihger clouds are of minor importance until they cover the whole sky (8/8), but best flights are performed with clear sky. High clouds base is favoured for

long flights, however it showed a correlation to certain launch spots. So given a low base, most flights are performed in the flatlands.

- View
  The farer the better because solar radiation is damped by the particles.
- Precipitation In wet conditions energy of the sun is wasted for vaporescence and the clouds base is lower.

A.3 Regtherm

Regtherm (regional thermal model) descends from Alptherm. It provides forecasts of thermal strength as well as other parameters like base height, clouds, wind direction and wind strength in the mixing layer. Calculations are mainly based on luvside soundings corrected by regional measurements. Forecasts are provided for different regions taking into account volume effects, average albedo, soil heat flux, soil moister and geographic location. Regions are linked according to valley wind systems.[1]

A.4 Tips for Pilots

Even better than having great algorithms to correct flight data is to have better raw data. The pilots themselves play an important part since they generate the data. Here some guidelines for pilots are given on how to create high quality data:

- Set the log interval of the GPS recorder to 2-3 seconds. Higher intervals than 10 seconds result in loose tracks making it impossible to detect circling. Smaller intervals lead to rounding problems since timestamps are created for full seconds.
- If a barometric GPS device does not perform automatic altitude calibration, set the barometric height manually before launch.
- Give the GPS device some time to properly boot up, find enough satellites and perform various self calibrations before launch, but also crop this part when uploading the flight to the computer.
- Upload all flights, also the small ones. A dummy account could be created to prevent social pressure.

[1] `http://www.shv-fsvl.ch/sg_archiv/wetter/de/0304.htm`, visited May 2010