Dealiasing Wind Information from Doppler Radar for Operational Use

A dissertation submitted to the
SWISS FEDERAL INSTITUTE OF TECHNOLOGY ZURICH

for the degree of
Doctor of Natural Sciences

presented by
MARC WÜEST
Dipl. Natw. ETH
born 20 December 1973
citizen of Switzerland

accepted on the recommendation of
Prof. Dr. H. Richner, examiner
Dr. J. Joss, co-examiner
Dr. W. Schmid, co-examiner

2001
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Abstract

A dealiasing technique for radar Doppler velocities based on a variational technique is proposed. The Doppler velocity image is dealiased region-wise by forcing continuity and overall agreement with a mean wind estimate. The latter constraint reduces the propagation of errors in space. The method estimates the quality of the dealiased regions by using the residual between calculated Nyquist numbers and their applied integer values. This dealiasing technique corrects the Doppler velocity images for use in a wind field retrieval under different meteorological situations.

The wind field can be retrieved from Doppler radar observations using the technique by Protat and Zawadzki (1999). This technique assimilates a model wind field to the radar observations but uses physical constraints and movement estimators to retrieve the missing (not measured) wind components. This thesis compares two concepts to eliminate spurious vectors when retrieving the wind field from Doppler observations. The first method is based on smoothing the radar data. The second method uses a smoothness constraint as part of the wind field model. Second order spatial derivatives of the wind field product are minimized. Two- and three-dimensional wind fields are retrieved from simulated radar observations, using different noise filtering techniques. The smoothness constraint eliminates spurious vectors more efficiently while reliably retrieving the wind field. Smoothing the radar data unintentionally dampens the characteristic wind variation. Applying the smoothness constraint is indispensable for the retrieval of the vertical wind velocity. It is recommended in general.

The proposed methods are implemented to investigate the dynamics of the winter storm Lothar on 26 December 1999. Severe damage happened in northern Switzerland around noon when a narrow cold-frontal rainband (NCFR) passed. The variational dealiasing is successfully applied to the images of the ETH radar. The three-dimensional wind field is retrieved using the described noise filtering configuration. Analyzing the dynamics of the NCFR reveals that - atypically for this meteorological system - the strongest winds are at the trailing edge of the rainband and collocated with the core regions of the NCFR. This explains the bands observed in the forest dam-
The application of the methods on Lothar demonstrates their potential for meteorological purposes.

The **applicability of a single-Doppler wind field retrieval** is investigated taking dual-Doppler wind fields as a reference. By undersampling the observations of the second radar, the influence of the resolution of supplementary wind field information is investigated. Both punctual as well as volume-averaged observations are used. An error analysis for the cross-beam wind component indicates a significant improve of the accuracy of the wind product by including even sparse information about the volume-averaged tangential wind component in the retrieval domain, whereas punctual information is less representative.

The variational dealiasing and the wind field retrieval algorithm by Protat and Zawadzki (1999) are implemented as a test platform at ETH to **operationally retrieve the wind field** from the Swiss radar network. The wind field retrieval technique is adapted for the use in Switzerland by adding a new lower boundary condition considering the topography and by combining both multiple- as single-Doppler elements. Experiments are run with both archived and real-time observations.
Zusammenfassung


Chapter 1

Introduction

1.1 Outline

This thesis consists of two previously published articles. The article


is outlined in more details and extended by additional experiments. It yields the content of Chapter 2. The article


is reproduced in its original form with minor changes in Chapter 3. The first chapter builds the broader context of the papers by showing the relevance for meteorological applications and analyses. It introduces the Doppler velocity together with its benefits but also its perfidies and the challenge of profiting from it. An analysis of the winter storm Lothar in 1999, which methods of this thesis are applied on, is presented in Chapter 4. Chapter 5 scrutinizes the applicability of a wind field retrieval with varying data availability. The findings of this thesis help to retrieve a reliable and accurate wind field. Its implementation for operational purposes with the Swiss radar network is presented in Chapter 6.
1.2 Weather radar basics

The development of radar (RAdio Detection and RAnging) instruments started during the 1930s after interesting anomalies were discovered in radio communications. Very soon the use for military purposes, e.g. aircraft detection, was recognized and pushed forward during World War II by several countries. From a radar’s point of view, an aircraft is primarily a scatterer (for electromagnetic pulses). Albeit the smaller size and by this the less efficient backscattering properties, precipitation particles are just another class of scatterers. For military purposes the echoes from weather phenomena are undesired in general as they hide aircrafts, but for the meteorology these echoes are of great value. Precipitation systems cast detailed and impressive echo structures onto the radar display which motivated researchers to study them. By the end of the war civil organizations and amongst them meteorological research institutes profited by surplus radar equipment of the military.

In order to balance adequately the backscattering strength, the range of measurements and the instrument costs, the typical wavelength of a weather radar is 1 to 10 cm. Such electromagnetic pulses belong to the class of microwaves, for which clear-air is relatively transparent. The wavelength is selected slightly larger than the maximum particle (scatterer) size to provoke Rayleigh scattering. This scattering type is physically well known and provides the best circumstances for quantitative interpretations of the echoes. The Rayleigh backscattering cross-section and by this the returned power of a spherical water drop depends on the particle diameter to the sixth power. One implication of this is that few large hydrometeors like hail cast back a much stronger echo than a large amount of small particles like drizzle. In a pulse volume, wherein a spectrum of hydrometeors act as scatterers, the former particles will dominate the received echo.

With this conventional weather radar technology, precipitation systems can be studied to gain information about their structure, movement and development. This is possible at high spatial and temporal resolution. Profiles along a single beam can be retrieved at frequencies higher than 1000 Hz and with a radial resolution of typically tens (vertically pointing) to hundreds (horizontally scanning) of meters. Given by averaging and the revolution of the antenna, a horizontally scanning weather radar can provide (PPI) images every few tens of seconds. With this favorable resolution, animations of a temporal series of reflectivity pictures help to estimate the immediate movement of the precipitation for nowcasting, i.e., precipitation forecasts for a range of approximately one or two hours.
1.2. Weather radar basics

Assuming the echo power is determined by the Rayleigh law, it is proximate and a widespread field of research to estimate the precipitation rate for radar reflectivity measurements. Many problems are affiliated with this, often related to representativity (height of the observation, pulse volume size, etc.). Nevertheless, the radar reflectivity is a powerful means at least for a more qualitative estimation of the precipitation rate.

1.2.1 The Doppler velocity

Modern radars are not only capable of measuring the power returned from a scatterer but additionally of providing information about the movement of the object along the radar beam, i.e. in the radial direction. Christian J. Doppler discovered that a moving object will shift the frequency of sound proportionally to the speed of movement. What is consequently known as the **Doppler effect** is true for electromagnetic waves as well, and applied for most of today’s weather radars. Albeit the fact that it has so far not been outlined to what object (air, cloud, droplets) the measured Doppler velocity can be attributed, it can be presumed, that valuable additional information about the scattering object is provided.

Let us reflect how the Doppler effect is explained physically and what the instrumental requirements are. An electromagnetic pulse from a radar transmitted with an initial phase of $\phi_0$ is returned with a phase

$$\phi = \phi_0 + \frac{4\pi r}{\lambda}$$

where $r$ is the distance to the scatterer and $\lambda$ the radar’s wavelength. The phase changes from one pulse to the subsequent pulse are given by

$$\frac{d\phi}{dt} = \frac{4\pi}{\lambda} \frac{dr}{dt}. \quad (1.2)$$

$dr/dt$ is the radial velocity $v$ of the object and $d\phi/dt$ the angular velocity $\Omega$. Using $\Omega = 2\pi f$ it follows for the frequency shift $f$ of a target moving relative to the radar that

$$f = \frac{2v}{\lambda}. \quad (1.3)$$

Given by the sinusoidal wave character the phase shift can only be determined within the range of a wavelength. The phase shift in radar technology is considered to be the
difference in angle between the point of interest and the nearest zero point of the wave, hence, the phase shift is a real number $-\pi < \frac{d\phi}{dt} < +\pi$. The ability of a Doppler radar to detect slight phase shifts depends critically on the system components maintaining a constant transmitter frequency and phase relationship from one pulse to the next. A lot of radars use coherent transmitters transmitting the same frequency and initial phase from one pulse to the next. In general this is realized by klystron transmitting tubes. Alternatively magnetron transmitting tubes cannot maintain the same phase but possess components to sample and store the phase of each pulse, such that they can be compared to the received signal.

For the determination of the phase shift a device called stable local oscillator (STALO) is employed in Doppler radars maintaining a stable frequency. The STALO signal is mixed with the transmitter frequency in a locking mixer and sent through a coherent oscillator for amplification while maintaining the original phase relationship. The STALO signal is also combined with the received wave in the receiver/mixer and amplified in the intermediate frequency (IF) amplifier. Both the received signal and the sample from the transmitter are processed in the phase detector.

It can be estimated from common radar parameters and target velocities that changes in the trigonometric signals are extremely difficult to be detected technically within a single pulse. Therefore, the target phase shift is measured over a longer time from echo pulse to pulse. In an ideal case with merely one target contributing to the echo, the phase shift and with this the Doppler velocity could be determined from two pulses. However, the natural complexity of the pulse volume, system noise, background radiation, side lobe returns etc. do not allow such a simple solution. Usually, a series of tens to a few hundred pulses are analyzed in an ensemble: a Fourier transformation or similar technique yields the Doppler spectrum from which the most significant peak is determined as the Doppler velocity (first moment of the Doppler spectrum). The identification of the significant peak is itself a big issue. Aside from the meteorological peaks, there often exist additional peaks, one of them from ground echoes (stationary targets) around zero velocity. Sophisticated techniques as the multi-peak analysis by Griesser (1998) can identify two to three peaks in the Doppler spectrum and distinguish between hydrometeorological peaks, ground echoes and clear-air echoes (for e.g. wind profilers). If the Doppler spectrum is noisy and no emphasized peak can be identified, the observation is marked as clutter (Section 1.4).
1.2. Weather radar basics

1.2.2 The Nyquist velocity

The ability to measure the radial velocity component of an object is a very powerful means for investigating the dynamics of a precipitation system (Doviak and Zrnič 1984), however, there are limitations. Because the phase shift is measured only within one wavelength, a larger phase shift is folded or aliased into this range. A phase shift of half the wavelength can e.g. not be distinguished from a phase shift of minus half the wavelength. This sets limitations to the measurement of the Doppler velocity. The maximum velocity $v_a$ of a Doppler radar can be unambiguously detected only within a range given by the velocity producing a phase shift of $\pi$ radians.

$$ v_a = \frac{f_a \lambda}{2} \quad (1.4) $$

The maximum frequency $f_a$ is given by $f_a = \frac{\text{PRF}}{2}$, where PRF is the pulse repetition frequency of the radar. The maximum unfolded Doppler velocity is also referred to as the Nyquist velocity $v_a$.

$$ v_a = \frac{\text{PRF} \cdot \lambda}{4} \quad (1.5) $$

Evidently, the Nyquist velocity could be increased by either enlarging the PRF or the wavelength. However, increasing the radar's wavelength is accompanied by a decreased sensibility for small scatterers and will require a larger antenna as well as higher financial means. On the other hand, enhancing the PRF will influence not only the Nyquist velocity but also the maximum unambiguous range $r_a$. $r_a$ is half the distance the wave travels between the time of two consequent pulses, thus $r_a = c/(2 \cdot \text{PRF})$ where $c$ is the traveling velocity of the wave. This relationship can be combined with (1.5). Figure 1.1, adapted from Rinehart (1991) visualizes the consequences of this equation.

$$ v_a r_a = \frac{c \lambda}{8} \quad (1.6) $$

(1.6) is the crucial relationship to be consulted when a radar is to be installed for operation. A solution satisfying both the needs for long range and high Doppler velocity has to be considered. Section 1.3 will demonstrate detours to this ambiguity problem by changing the pulse form of the radar transmission. The detours are of varying success and applicability. Alternatively, could we correct the Doppler velocity observations where the signal is folded, more weight can be set on the range. The correction of
Figure 1.1: Visualization of (1.6) showing the relationship between the Nyquist velocity and the unambiguous range for a selection of radar wavelengths (taken from Rinehart (1991)).

Doppler velocity ambiguities, after the scans are taken, is called dealiasing (or unfolding). In Section 2.2 we will outline existing dealiasing techniques and Chapter 2 will propose a new variational dealiasing technique.

### 1.3 Range velocity ambiguity mitigation techniques

A number of techniques have been developed and implemented in radar systems to avoid range velocity ambiguities. Keeler et al. (1999) gave a review of existing techniques, some of which will be mentioned in the following and sketched in Figure 1.2. From (1.6) in Section 1.2.1 an increase (improve) of the Nyquist velocity is known to be feasible only while shortening the radar range. Consequently we are looking for a way to enlarge the product \( r_a r_a \) at reasonable cost. This can be realized by transmitting appropriate waveform patterns.

The dual / separate PRT waveform in Figure 1.2a requires two constant, separate but independent waveforms: the long PRT allows unambiguous power measurements to long ranges and the short PRT allows adequately large unambiguous velocity determination. Alternatively, two scans can be performed at each elevation, a long PRT scan for reflectivity and a short PRT scan for velocity, or, two radars can share a common
antenna, which is also known as a dual-frequency approach (Glover et al. 1981). This technique allows an excellent clutter elimination, but is also clearly more expensive: two separate transmitters and receivers are required. Moreover, restricted frequency allocations near the radar bands have limited such applications.

A detour to this, where only a single transmitter and receiver is used, is the so-called batch mode in Figure 1.2b (Zahrai and Zrnic 1993). A short PRT is used for velocity measurements and a long PRT for reflectivity estimates (Hennington 1981). For example, several pulses at a short PRT are first transmitted, followed by a clearing period (no transmission) and then one or two pulses separated by a long PRT for the reflectivity estimate. The basic assumption is that the PRT for the reflectivity is sufficiently long such in order no second trip echoes to occur. In a similar manner (combined PRT, Figure 1.2c) reflectivity pulses (long PRT) can be transmitted at frequency $f_1$ replacing one of the short PRT pulses at frequency $f_2$. The short PRT velocity estimates will have two classes of range aliased echoes, those overlaid with the first trip echoes and those not overlaid with the first trip echoes. When there is no overlap, the velocity estimates can actually be assigned to the correct range. When first and higher trip echoes are overlaid and one dominates the other in power by 10 dB or more, then the velocity of the strong echo can be correctly estimated. The disadvantages of this batch technique are 1) the loss of velocity data where first and second trip echoes are overlaid and powers are nearly equal, 2) the technique may preclude the use of effective clutter cancelling and 3) the data acquisition time is increased because the long PRT pulses are unusable for making velocity estimates.

Figure 1.2d depicts the spaced pair pulse waveform (Doviak and Sirmans 1973) in which velocity information is retrieved from pulse pairs separated by $T_r$, but the pairs are separated by a time adequate to prevent overlaid echo. However, the overlaid echo on the second pulse contaminates the velocity estimate thus the velocity of the second trip echo cannot be measured. The range velocity relationship improvement can be made arbitrarily large, but the velocity estimates tend to be of low quality because few independent, spaced pairs are available.

Multiple PRT and PRF techniques can be used to dealias velocities. The nomenclature of Atlas (1990) for these two techniques is adapted. Multiple PRT means changes of the PRT on a pulse-to-pulse basis. In the dual PRT (or staggered PRT) method (Figure 1.2e) the two PRTs usually are in ratios of either 3/2 or 4/3. The first lag complex autocorrelation for each PRT is calculated and averaged over a number of pulses. Then, the expanded velocity $\tilde{\upsilon}$ is calculated from
Figure 1.2: Pulsed waveforms proposed for range velocity ambiguity mitigation, adapted from Keeler et al. (1999). Arrows denote single pulses, if shaded, they are transmitted at secondary frequency $f_2$. 

\[ \hat{v} = \lambda (\theta_1 - \theta_2) / [4\pi (T_2 - T_1)] \]

where $\theta_1$ and $\theta_2$ are the phase shifts for each PRT and $T_1$ and $T_2$ the two PRTs. The corresponding unambiguous velocity is

\[ v_u = \pm \lambda / [4 (T_2 - T_1)] \]

Following this expression, a $3/2$ PRT ratio yields an unambiguous velocity being twice the one corresponding to the short PRT. For a $4/3$ PRT ratio the expanded velocity interval is three times this value. There remains the question, why no further expansion is done: since the variance of the expanded velocity estimate is based on the difference between the two fundamental estimates, its variance is roughly proportional to twice that of each fundamental estimate. This is less of a problem because the expanded velocity needs to be used only to roughly dealias the two fundamental estimates. The velocity estimate can be improved by averaging the two velocity estimates to get the final estimator, provided that both velocity estimates have been correctly dealiased. This
1.3. Range velocity ambiguity mitigation techniques

averaging technique provides an estimator which uses all available pairs of consecutive pulses, rather than half the available pairs. Since the dual PRT technique dealsaises velocities by a large factor, the radar can be operated at a lower PRF and thus have a larger unambiguous range. Doviak and Zrnić (1984) point out another advantage of the dual PRT technique, i.e., second trip echoes will be incoherent or ‘whitened’ and thus not bias the first trip velocity estimates.

A disadvantage of the dual PRT technique is the difficult implementation of standard clutter filters. This can be overcome for some filtering schemes by using a dual PRF method (Figure 1.2f) wherein a sequence of pulses is collected at each of two PRFs and then each sequence is processed separately. The data processing is identical to the standard pulse pair processing except that the velocity from the previous sequence is used along with the velocity from the current sequence to dealias the current velocity. The sampling statistics are similar to the pulse pair, except that for this technique to be viable the mean velocity change between sequences must be small.

Because the PRF is fixed while each batch is collected, the dual PRF technique can employ a batch processing clutter filter such as an FFT filter. Because the basic dual PRF processing is essentially the same as standard pulse pair processing at a constant PRF, it is easier to implement on an existing system. Unfortunately, the dual PRT feature of ‘whitening’ the second trip echoes is lost when dual PRF is used.

Some of the range velocity ambiguity mitigation techniques mentioned were implemented in operational weather radar systems. The Terminal Doppler Weather Radar (TDWR) (Crocker 1988) is a C-band radar automatically selecting a PRF to minimize overlaid echoes in an airport sector. For the weather radars in the USA investigations have been started for a feasible implementation of an RV mitigation technique (Sachidananda et al. 1997, 1998) into the NEXRAD (Next Generation Weather Radar) system. Unfortunately, the mentioned changes in the pulse waveform are accompanied by a loss of information and even if the RV ambiguity is mitigated, the quality of the observation suffers. In addition to this, many radar systems are operated with a fixed scheme which is optimized for certain purposes. Very often this scheme is optimized for the observation of the reflectivity as a measure of precipitation, whereas the Doppler velocity is a secondary measurement enjoying less importance (and application). For these reasons the Doppler velocity image is frequently aliased and techniques to correct this are necessary. Chapter 2 will present existing dealiasing techniques and propose a new variational dealiasing algorithm.


1.4 Clutter filters for radar observations

The purpose of operating a weather radar is to observe meteorological phenomena. Amongst these are mainly precipitation systems, but also non-precipitating clouds for sensitive systems at short wavelengths. Wind profilers at long wavelength (around 1 GHz) are able to observe changes in the fraction properties in clear air. Not completely compatible with this objective, echoes from non-meteorological targets frequently contaminate the radar image. A first source of undesired echoes are cast back from side lobe signals. Although a good antenna reflector manages to focus the majority of the pulse energy onto the main beam, there are 'leaks' where energy escapes in directions off the focus. Echoes from the side lobes falsify the radar image, but are often weak or from stationary targets. Thus they merely fudge the signals in the vicinity of the radar. They are relatively difficult to eliminate since they are not coherent and a superposition of several echoes. In comparison, main lobe clutter is easier to detect because of a clear peak at zero phase shift. The earth surface, buildings, trees etc. give a strong echo if they are hit by the radar beam. The elevation of the antenna is aimed high enough to be over the horizon, but in regions with distinct orography this cannot always be accomplished. Another uncertainty is the variation of the path of the radar main lobe through the atmosphere with the stratification of the refraction index. When a temperature inversion is present, the beam is deflected towards the earth surface and the risk of hitting the ground is enhanced. The term anomalous propagation is often abbreviated as anaprop. Aside from stationary ground-based targets, aircrafts, birds and insects can contaminate the image of a radar used to estimate precipitation.

The mentioned non-meteorological targets often attract attention by returning a noisy Doppler spectrum or a clear peak at zero velocity. These echoes are called cluttered and to be marked and eliminated as such. Several strategies are conceivable for reducing clutter in the radar image. The use of a combined scheme is recommended by Joss et al. (1998). They propose to use high range resolution and to take advantage of the rapid de-correlation of clutter echoes in space, seeking clutter-free returns close to clutter echoes. This allows to average over a number of clutter-free range bins (gates) for a single product pixel. A single clutter-free bin can be sufficient for the estimation of one pixel, from which a good clutter elimination and data availability follows. For the Swiss radar network (SRN) the signal processing algorithm for the single bins (gates) is based on a decision tree classification system (Lee et al. 1995). All data collected from a bin is used to classify the signal as precipitation, clutter or system noise. The decision tree (Figure 1.3) consists of seven stages:
1.4. Clutter filters for radar observations

Figure 1.3: The seven stage decision tree for the elimination of ground clutter in the Swiss radar network. The figure is taken from Joss et al. (1998).

1) The processing of a signal is terminated if the signal power is lower than a threshold set a few dB higher than the system noise level. The clutter map can be decremented since no signal exists and hence no clutter is present.

2) The wide-band noise test is performed in the Doppler channel after a valid signal (above receiver noise) was detected in the test above. If the coherence is high enough and the wide-band noise level lower than a second threshold value, the tree is continued. If not, the bin is marked as clutter, the clutter map is incremented and the processing for this gate is terminated.

3) The velocity algorithm is performed on signals which did not get a conclusive answer from the first two tests, and hence are known to be significant in magnitude and coherent. The test classifies a received signal as a usable precipitation measurement if the signal velocity is outside an adjustable band around zero ve-
locity. Since this indicates a movement of the echo, the estimate is marked as precipitation, the clutter map is decremented (since no clutter was observed), and processing for that gate is terminated. Lee et al. (1995) name this the dominant test to detect weather.

4) Two statistical clutter filter tests are applied to signals known to be coherent but around zero velocity. The tests are to determine the probability of the signal being precipitation, based on the signal probability distribution. A first statistical test is applied to investigate the rate of fluctuation of the echo, assuming precipitation echoes to fluctuate faster (more change from pulse to pulse). Entering the second statistical test we know the signal is changing fast. To avoid classifying range bins as precipitation because of clutter entering (or exiting) the main beam, the two-lag difference is applied: echoes with a strong and continuous increase (decrease) are marked as clutter. According to Geotis and Silver (1976) incoherent clutter detection using the mean-difference algorithm permits 70% of the clutter signals to be rejected with no loss in weather echoes, for a scanning antenna. The rejection rate is much higher for the stronger echoes, which concern most. The remaining 30% of the echoes contaminated by clutter are mainly weak, causing only a negligible bias.

5) By checking the vertical gradient - i.e., from an elevation angle to the next - of signal power second-trip echoes and anomalous propagation are to be detected. If the observed gradient is larger than the climatological norms (also considering bright band effects), the observation is likely to be misplaced and marked as clutter.

6) As a last resort, for signals which have been found to be significant in magnitude, of zero velocity and with statistics which could represent precipitation, an adaptive clutter map is consulted, basically a counter for the result of the tests for each pixel position in the radar image. The clutter map is updated with every pass through the decision tree but only consulted when none of the tests was conclusive for a signal. The clutter map thus describes the recent past and helps to identify an observation at last resort, when no other test was conclusive. If the recent past of the gate in question has evidenced significant clutter, it is marked as clutter, otherwise the echo is accepted as precipitation. This clutter map is needed far less frequently than clutter maps in earlier systems, where it was the only way to eliminate clutter.

The algorithm proposed by Lee et al. (1995) is applied operationally for the Swiss radar
network. Further effort to improve this scheme was done by Germann and Joss (1999) and the resulting improvements were implemented on all three Swiss radars in summer 1999. The new decision tree includes a neighbor-test: gates with non-zero velocity only pass the clutter elimination algorithm if the adjacent gates have low clutter map entries. In addition to this, a clutter map leak (to avoid dead-ends and positive feedbacks in the dynamic clutter map) and a speckle filter were added.

We expect the non-meteorological targets to be eliminated the best way feasible with the clutter filters. Germann (2000) states from experiments (volume scans during fine weather), that the clutter of 3% in radar observations without elimination can be reduced to 0.07% with the improved clutter filter decision tree. Nevertheless, remaining noise needs to be accounted for and meteorological information might be erroneously eliminated by the clutter filters.

Figure 1.4: Sample PPI of Doppler velocity (right) and reflectivity (left) taken from the Albis radar (MeteoSwiss). Note how values with zero Doppler velocity are eliminated by the clutter filter in both images. This can yield a problem for the identification of the zero velocity lines in the dealiasing procedure (Chapter 2).

A problem which can arise when the filter parameters are not ideal for a given meteorological situation is that too many bins with zero Doppler velocity are marked as clutter. Figure 1.4 shows an example, where in fact a zero velocity line exists in a SW wind situation. The filters eliminate large portions of the zero velocity bins. For subsequent applications in the thesis, the missing of the zero velocities is undesired yet not critical.
1.5 Velocity information from radar data

Amongst all the technical limitations it should not be overlooked that weather radars are supposed to provide observations from precipitation phenomena. The sensitivity is not sufficient to measure clear-air echoes in general. Hence, applications basing on the radar observations are primarily limited to precipitation systems. In the following, several aspects concerning the velocity information available from radar observations are discussed.

1.5.1 Doppler spectrum

It is obvious from Section 1.2.1 that the Doppler spectrum obtained from a Doppler radar reveals important new information about a scanned pulse volume, if compared to a conventional non-Doppler radar. Whereas the latter merely provides an echo power, an integral value for an enormous amount of scattering particles, the Doppler spectrum allows to carefully distinguish between types of scatterers. This allows to filter out observations cluttered by returns of ground targets (side lobes etc.). The characteristics of the Doppler spectrum can be interpreted to estimate the variability of scatterers or the shear and turbulence in a pulse volume (Wüst et al. 2000b). In order not to store the entire spectrum, the width of the Doppler spectrum (spectral width, second moment) is often calculated by the radar computer and provided as a third parameter besides the reflectivity and the Doppler velocity. Using vertically pointing radars the Doppler velocity is mainly determined by the fall speed of the particles and overlaid by the vertical airflow. If the vertical airflow is negligible as often observed in stratiform precipitation, the Doppler spectrum allows for estimating drop size distributions or distinguishing between snow particle types, if parameterizations for the fall speed are consulted.

1.5.2 Difficulties and errors

Apart from using the Doppler spectrum for filtering the radar signals, the Doppler velocity provides a measure for the radial movement of the echo which is characteristic (or dominant) in the scanned pulse volume. It is proximate to aim at taking advantage of this observation to determine the movement of the echoes by any means, providing tools for wind analyses and nowcasting. However, using the Doppler velocity suffers from two major drawbacks. On the one hand it can be folded (aliased) if the phase shift exceeds the Nyquist range, on the other hand it provides information about the movement
of a scatterer only in the radial direction (parallel to the beam). In the worst case, the echo movement significantly exceeds the Nyquist velocity, dealiasing becomes difficult (multiple folding) and we need to be prepared for feasible errors in the radial velocity of the order of twice the Nyquist velocity (20 to 30 m/s). These errors need to be detected and eliminated since they falsify any product stemming from these Doppler velocities.

The movement of the echo tangential (cross-beam) to the radar beam cannot be measured or determined from a single PPI scan. As shown in the following section, estimates of the cross-beam movement are possible by tracking the echo from one PPI to the following. This estimate can serve as a proxy for a direct measurement of the missing movement component but needs to be handled with care. An error analysis considering the cross-beam wind component will be given in Chapter 5.

### 1.5.3 Tracking echoes

There are two principally different approaches conceivable for the estimation of the movement of radar echoes. One of them is to track the echo structure in time and to determine a movement vector with e.g. a best-correlation technique. It is discussed in this paragraph. The human eye manages that task very reliably, even for complex images. Letting a machine do the same task requires some computing power and an appropriate spatial and temporal resolution model. Rinehart and Garvey (1978) presented a technique called TREC (tracking of radar echoes) to determine the storm motion by finding the best correlation between two successive radar images. For this purpose, the two radar images are shifted relative to each other whilst continuously calculating the shifted correlation. The maximum correlation determines the horizontal echo shift caused by the storm motion, from which a velocity vector can be estimated by the time difference of the scans. This method was expanded with the continuity equation for smoothness of the vectors by Li et al. (1995). The technique splits the radar image into boxes, which are individually tracked and yield the resolution of the tracking product. The box size and data grid resolution was optimized by Mecklenburg et al. (2000) recommending a box size of approximately 20 to 30 km for the Swiss radar network. Techniques like TREC and its successors do not require the observation of the Doppler velocity.

It must be emphasized that the motion of a storm or its echoes does not necessarily correspond to the wind field. The echo movement is a combination of the drive by the wind field and the growth/decay of precipitation particles. If the box size is selected large enough to cover single cells with one box, there can be deviations between the
environmental wind field and the storm motion. In addition, tracking techniques are often applied to a maximum reflectivity image of a volume scan (a volume scan means that the radar antenna carries out full revolutions at a set of elevation angles). For each horizontal position, the maximum reflectivity value in the vertical column is then considered in the radar image and the height information is lost. Depending on the vertical wind shear these methods are susceptible for errors.

1.5.4 Wind field retrieval

The second approach to determine the movement of radar echoes primarily bases on the observation of the Doppler velocity. Assuming that precipitation particles move with the wind in the horizontal dimensions, the term wind field retrieval is commonly used for this category of methods. This requires the air to exercise a drag on the precipitation particles, by which they react upon changes in the horizontal wind. In the vertical direction up- and down-winds act on the particles similarly, however, gravity overlays the fall speed in the Doppler measurements. This needs to be considered since fall speeds are often larger or of the order of vertical wind speeds. Section 3.5.2 will mention the implications. Note that in addition to this the Doppler velocity will favorably represent the speed of the large particles in the scan volume, if expecting Rayleigh scatterers (the reflectivity grows with the diameter to the sixth power).

If the aforementioned assumption is accepted - precipitation particles horizontally move with the wind - the Doppler velocity observation from a feasibly horizontal scan yields one (radial) component of the wind vector at each gate. This provides highly resolved wind information with the drawback that only the radial component is measured. Several resorts to this have been found, e.g. the velocity-azimuth-display (VAD) technique, described by Browning and Wexler (1968) or Lhermitte and Atlas (1961). They assume the wind components to vary linearly in the horizontal direction and calculate the mean wind at certain heights with a second-order Fourier expansion with respect to the azimuth. The volume velocity processing (VVP) method (Easterbrook 1975, Waldteufel and Corbin 1979) is similar to the VAD but carries out a multivariate regression fitting a wind model to the observed radial velocities with different functions. Both methods provide a mean vertical wind profile, which is often taken to be representative for the environment of the radar.

More sophisticated models allow to retrieve the two- or three-dimensional wind field at the resolution of the observations. They combine the Doppler radar observations with physical constraints, whereby missing information can be modeled (Tuttle and Foote
1.6. Lothar: challenging Doppler velocity observations

If only the observations from one Doppler radar are available, the missing cross-beam wind component needs to be estimated from supplementary wind field information. This can origin from a radio sounding, from a VAD, a reflectivity tracking algorithm or another appropriate source. In a multiple-Doppler radar configuration (Ray et al. 1979) or a bistatic system (Wurman et al. 1993) the horizontal wind components can be retrieved accurately thus allowing for the determination of the vertical wind with the help of the continuity equation (Sun et al. 1991, Protat and Zawadzki 1999). By including boundary conditions and corresponding physical constraints, thermodynamic variables are retrieved interacting with the three-dimensional wind field following Gal-Chen and Kropfli (1984). Crucial for all these applications is the aliasing of Doppler velocities. The lower the Nyquist velocity is, the more frequently aliasing happens. Without correct dealiasing a wind field retrieval and any other product generated from Doppler velocity data is not conceivable.

In contrast to a common tracking technique a wind field retrieval basing on the Doppler velocity observations can give insight to the internal structure of a storm or cloud at the resolution of the radar observations. The boxes which a tracking technique works with limit the resolution. Moreover, the wind retrieval lets distinguish between storm movement and the flow of the particles. Due to the high spatial and temporal resolution a wind field retrieval from Doppler radar data is favorable for analyzing the (thermo-)dynamics in precipitation systems. Besides the research purpose it allows the initialization of numerical weather prediction models, as it is currently investigated in the COST-717 committee (Lindskog 2000). Other applications are wind shear detection systems for airports or operational gust front warnings (Wilson et al. 1984).

1.6 Lothar: challenging Doppler velocity observations

The previous sections outlined various technical aspects being important when operating a weather radar. The product dispensed by the radar computer after the mentioned filters are applied is rather illustrative and can be visualized with images of the echo power (usually scaled in dBZ, see Appendix A), of the Doppler velocity and of the width of the Doppler spectrum (often interpreted as a measure for the wind shear or turbulence). It was further summarized that several methods exist to retrieve information about the wind field in the echo area. In order not to lose sight of meteorological applications, we introduce Lothar as a spectacular, yet serious meteorological event from a radar’s point of view in this section. This storm gives motivation for pursuing the objectives set for this thesis. A detailed analysis of Lothar will follow in Chapter 4.
The winter storm *Lothar* struck on 26 December 1999 and devastated many regions in northern France, southern Germany and northern Switzerland. There were fatal casualties in all three countries (14 people were killed during the storm, 15 when clearing the damaged forests) and the wind damaged enormous amounts of infrastructure and especially forests. It is estimated by WSL and BUWAL (2001) that approximately $12.5 \times 10^6$ m$^3$ wood was broken or uprooted in the Swiss forests alone. The total damage to forests, infrastructure and private property is estimated to amount to approximately $1.78 \times 10^9$ CHF. The storm originated as a shallow low-level cyclone over the western Atlantic and traveled towards Europe with moderate intensity. The dynamical aspects of the storm on a synoptic scale are investigated by Wernli et al. (2001). The eastward translation of the cyclone was accompanied by continuous and intense condensational heating. A suitable arrangement of these features lead to the rapid formation of a narrow and deep tropopause fold. During the most intensive period a tower of positive potential vorticity existed. The evolution of meteorological fields on the mesoscale over northern Switzerland was successfully simulated with the high-resolution MC2 model by Maurer (2000). However, that simulation failed to replicate the narrow cold-frontal rainband associated with the most severe winds and its internal dynamical structure. Herein, the mesoscale properties of *Lothar* will be scrutinized by means of Doppler radar observations. The period when the storm actually affected Switzerland lasted from about 0900 to 1130 UTC (1000 to 1230 LT). The most severe winds near Zürich were observed around 1045 UTC. The focus of this study will be set on the radar observations around this time.

Figure 1.5 shows the reflectivity and Doppler velocity PPI of *Lothar* at 1044 UTC. The PPI was scanned with the ETH C-band radar on Hüningerberg, Zürich, at an elevation of 1.5° (the radar antenna is at 600 m a.s.l.). Regarding the reflectivity pattern we note a banded structure with core regions and gap regions as they are often observed in narrow cold-frontal rainbands (NCFR) (Hobbs and Persson 1982). In order to investigate the origin of this structure, a wind field analysis is aimed at, favorably taking advantage of the observations of the Doppler velocity. However, the PPI in Figure 1.5 reveals the obstacles associated with the Doppler velocity measurements. The Nyquist velocity of the ETH radar of 16 m/s is exceeded at many places in the Doppler velocity image. There, the radial velocities are aliased. We can even presume two-fold aliasing indicating the observation of radial velocities of over 48 m/s in magnitude.

An even more delicate task is to correct the Doppler velocities observed with the MeteoSwiss C-band weather radar on Albis. The Nyquist velocity of the 1.5° PPI is 8.25 m/s being a factor of approximately five smaller than the expected maximum wind speeds during *Lothar*. The Doppler velocity image one minute after the ETH PPI scan
Figure 1.5: PPIs of the reflectivity (left) and Doppler velocity (right) scanned by the ETH radar on Hänggerberg, Zürich. The radar antenna is marked with the triangle in the center of the image and is installed at 600 m a.s.l. Dashed circles mark the PPI height of 1 km (smaller circle) and 2 km a.s.l. (larger circle).

shown above is depicted in Figure 1.6. Retrieving valuable and reliable velocity information from the image appears challenging.

The intensity and severity of Lothar gives the motivation to correct the Doppler velocities and to determine the wind field from the radar data in order to study this intensive storm. Recalling the damage potential of Lothar a warning system and hence an automatic and reliable procedure for the dealiasing and wind determination is pending. Chapter 4 will apply methods found in this thesis to the radar data of Lothar.

1.7 Glossary

The previous sections introduced several terms and methods relevant for working with weather radars. The following brief glossary will collect and summarize frequently used terms of this thesis. Some important methods will be distinguished in the consequent paragraphs.

- **Doppler velocity** - From the phase shift of a radar echo the movement of the scatterers from pulse to pulse can be estimated. This can be interpreted as the radial velocity of the scatterer, though folding of the signal at the Nyquist velocity can
Chapter 1. Introduction

Figure 1.6: PPIs of the reflectivity (left) and Doppler velocity (right) scanned with the MeteoSwiss radar on Albis, near Zürich. The radar antenna is marked with the triangle in the center of the image and is installed at 970 m a.s.l. Dashed circles mark the height of 1 km (smaller circle) and 2 km a.s.l. (larger circle).

falsify the signal.

- **Nyquist velocity** - A phase shift in a radar signal cannot be unambiguously interpreted. Adding multiples of the wavelength leads to the same measured phase shift. Since the Doppler velocity is determined from a phase shift, the radial component of the scatterer’s movement is folded when reaching the Nyquist velocity, i.e., the maximum unambiguously measurable radial velocity. This undesirable effect needs to be avoided (pulse characteristics) or corrected (dealiasing).

- **Clutter** - The pulse volume of a radar signal, growing with the square of the distance from the antenna, impacts a large number of scatterers, all contributing to the composite echo. If the composite projects a Doppler spectrum with an outstanding signal of a type of hydrometeors, it is valuable for weather interpretation. We aim at filtering out an observation as clutter if the composite appears to be influenced by too large a variety of (non-meteorological) scatterers thus yielding a non-interpretable Doppler spectrum.

- **Noise** - In this thesis, noise plays a central role and a specific definition is necessary. We use the term *noise* in the Doppler velocity observations for the randomly distributed errors superimposed on the real radial velocity value. The Doppler velocity image, even if showing a coherent echo structure and providing a valuable
first impression of the flow, will be affected by instrumental and technical errors
(receiver, spectral moment estimation, dealiasing) as well natural variability, all
avoiding a perfectly smooth image. In addition to this, isolated gates (pixels) in
the Doppler velocity image are of dubious representativity and hence are to be
erased as *speckle*.

- **Gate** - Radar observations are taken from electromagnetic pulses returned by
scatterers along the radar beam. This determines a radial resolution. One ele-
ment along the radial is also called a *gate*. Since radar observations are often
displayed as (polar) images, a gate can correspond to a *pixel*.

- **PPI** - Weather radar antennae usually perform 360° revolutions at constant el-
evation to scan an image of the environment. These scans have quasi-conical
topology and can be displayed as a polar or (transformed Cartesian) image called
*plan-position-indicator* (PPI).

- **VAD/VVP** - Methods to estimate the mean vertical wind profile from Doppler radar
observations. See explanations in Section 1.5.4.

- **Wind field retrieval** - The modeling of the wind field in two or three dimensions by
considering radar observations. The latter can be reflectivity data from which pat-
tern recognition determines a movement, or Doppler velocity data which provide
one component of the wind vector. Several methods are summarized in Section
1.5.4.

Section 1.5 listed several techniques for retrieving the wind field from radar data. In this
thesis the technique of Protat and Zawadzki (1999) - whose fundaments lie in Laroche
and Zawadzki (1994) - is treated. It was installed and adapted for the use with the
Swiss radar network and the Doppler radar at ETH Zürich as well as for the Swiss oro-
graphic environment. The technique of Protat and Zawadzki (1999) was selected since
it represents a modern technique and the nature of the variational analysis allows for
uncomplicated algorithm extensions, i.e., the inclusion of new observations and design
of new constraints.

A detailed explanation of the wind field retrieval algorithm will be given in Chapter 3.
Its integration as an operational tool will follow in Chapter 6. Here, we schematically
preview the organizational flow of a wind retrieval, as it is shown in Figure 1.7. The flow
chart sketches the abbreviated data processing starting after the first and the second
moment of the Doppler spectrum are determined. The wind field retrieval algorithm in
particular bases on data assimilation, i.e., it is the interface between the observations
and physical constraints. These need to be fulfilled as closely as feasible, thus the variables are varied systematically until the optimum state is reached. It is of paramount importance for the work in hand to distinguish between different stages and concepts of filtering radar observations.

- The purpose of the clutter filter is to eliminate non-meteorological observations. Section 1.4 gave an overview how this is done in the Swiss radar network. The product after the clutter filter is applied consists of observations which still be affected by statistical or instrumental uncertainties.

- The dealiasing algorithm corrects folded Doppler velocity values and thus changes their finite value by fixed amounts, multiples of twice the Nyquist velocity. Hence, it does not affect the reflectivity observations. We will show in Chapter 2 that prior to the dealiasing and for performance reasons a so-called five-neighbor filter is recommended. It erases speckle in the radar image and smoothes the edges of the echoes.

- Depending on the application for the Doppler velocity, a data smoothing can be carried out. Since the Doppler velocity image remains noisy after the clutter filter and the dealiasing, smoothing the data might provide more useful fields for numerical analyses. Whether the latter statement is correct will be examined in Chapter 3.

- A completely different approach of noise filtering in wind field retrievals is to leave the observational data unchanged, but to smooth the model wind field being assimilated to the observations. In the wind field retrieval algorithm of Protat and Zawadzki (1999) this is done with a smoothness constraint (Chapter 3).
1.8 Objectives of this thesis

This chapter outlined some difficulties encountered when observing the Doppler velocity of meteorological phenomena with a weather radar. The quality of the measurements depends on technical parameters as the radar antenna, the scan strategy and the pulse form, as well as on the meteorological and environmental conditions. There are a variety of errors. These need to be considered and filtered when retrieving the wind field in order to obtain a wind field, which represents all characteristic features of the flow and which is a suitable and applicable product.

This thesis sets its focus on the filtering of the velocity information when retrieving the wind field from Doppler radar data. Reliable and adequate wind fields are to be retrieved for post-analysis of meteorological events as well as for operational purposes. Five specific objectives - listed in the following - are treated in particular in this thesis. The objectives include different types of scientific work, which are 1) the development of a new (correction) algorithm, 2) the optimization of a wind model based on simulation experiments, 3) the analysis of the dynamics of a meteorological event and 4) the implementation of an operational tool.

- **Algorithm development** - A crucial part in the process of a wind field retrieval is the aliasing of the Doppler velocities. Without correct dealiasing, the retrieval of the wind field may contain important errors. Aliasing effects can reach the order of magnitude of natural wind shears. Therefore sophisticated techniques need to be found to distinguish between artificial (instrumental) and natural (meteorological) variations. Because of the geographical and geometrical correlation and the limited number of feasible discrete values of the aliasing a correction is feasible. This thesis presents a robust *dealiasing technique* based on variational analysis in Chapter 2.

- **Model optimization** - Different user groups can take advantage of a good knowledge about the wind field. Warnings for wind gusts, the initialization of numerical weather models and nowcasting of precipitation systems may profit. For applications the retrieved wind field should show the characteristic structure of the wind field and simultaneously hide instrumental effects and statistical noise. In order to reach this goal, the two different *noise filtering* approaches from above are useful (*data smoothing* and the application of a *smoothness constraint*). This thesis will judge the two techniques after applying them in the wind field retrieval technique in Chapter 3.
Chapter 1. Introduction

- **Meteorological analysis** - The application of the described procedures is demonstrated with the case study of the winter storm Lothar on 26 December 1999. The devastating character of the outrageous wind peaks on this day are a challenge for an operational wind field retrieval leading to a gust warning. The meteorology of the dynamics of Lothar will be discussed in Chapter 4.

- **Simulation** - Chapter 5 will judge the reliability of deriving the wind field from a single Doppler radar. Though radar networks became denser during the last decades, combining the Doppler velocity observations from multiple radars is geographically constrained to relatively few areas. Furthermore it will be investigated, what profit supplementary wind information can give.

- **Operational Application** - The wind field is planned to be retrieved from the Swiss radar network on an operational basis. This thesis will contribute to an accurate and reliable wind field by using the methods mentioned above. Chapter 6 will outline its implementation in an operational framework, currently used in an experimental platform.
Chapter 2

Variational Dealiasing

2.1 Introduction

From Chapter 1 we know the observation of the Doppler velocity can be affected by the effect of velocity aliasing (folding). Depending on the Nyquist velocity $v_a$, aliasing occurs at varying frequencies and might be avoided with a mitigating waveform pattern (Section 1.3). However, in general aliasing happens and must be corrected. Considering that the Nyquist velocity is of the order of observed wind speeds, overlooking aliased Doppler velocity observations would infer large errors.

The Nyquist number is an integer factor describing by what multiple of the Nyquist interval an observation is to be shifted in the Doppler velocity to correct the aliasing. A Nyquist number which equals zero indicates a datum which is not folded.

$$v_r = v_M + 2nv_a$$  \hfill (2.1)

In (2.1) $v_r$ is the corrected radial velocity, $v_M$ the observed and feasibly folded Doppler velocity and $n$ the Nyquist number.

We believe that the human eye combined with the experience of a meteorologist operator is still the most secure means to dealias Doppler velocities, yet not an economical or operationally applicable means. The human eye captures the Doppler velocity image as a whole and easily identifies and corrects aliased regions in the image, if the latter is colored suitably. Taking this intuition as a paragon we develop a new variational technique for dealiasing Doppler velocity images. The algorithm can be applied both to polar as to Cartesian PPI (plan-position-indicator) data. Minor modifications concerning the coordinate system are necessary for the environmental wind.
Chapter 2. Variational Dealiasing

2.2 Existing Doppler velocity dealiasing techniques

The observation of the Doppler velocity can be processed to any wind product only if the aliasing is corrected (or not present). The danger of aliasing is of course lower for radars tuned for a high Nyquist velocity. In fact, could minor errors be taken in account, a sumptuary dealiasing technique might be renounced provided that the wind speed is lower than the Nyquist velocity for most events and the majority of scanned gates. The latter is conceivable for S-band radars (approximately 10 cm wavelength) operating a high PRF. C-band radar networks, like the Swiss radar network, suffer from Nyquist velocities easily exceeded by wind speeds.

Several methods have been investigated to tackle the dealiasing problem since the late 1970s. Roughly, automated methods can be distinguished from interactive techniques, where a human operator controls the process (Bargen and Brown 1980). The focus in this chapter will be set on an automatic dealiasing technique. Considering operational generation of a wind product at the temporal resolution of the radar scans and an order of magnitude of $10^5$ gates observed per PPI scan, any kind of human interaction is unthinkable. Automatic or operational dealiasing techniques have become viable when computing power and memory allowed for it and the ongoing development will permit more complex algorithms.

The simplest approach to dealias Doppler velocities is to enforce radial continuity on each individual radar beam. Each range gate is compared to its neighbors and corrected with an integer Nyquist number minimizing the shear. This procedure is sensitive to noise, though, and errors can propagate through the beam. Ray and Ziegler (1977) developed a more robust technique which requires the radially sampled velocities to be normally distributed about their mean velocity. The proper Nyquist interval can be determined by requiring a non-normally distributed sample of velocities to be corrected such that a normal distribution is achieved. In cases where severe aliasing causes a large variation of velocities and biases the sample mean, this method can fail. The interactive method of Bargen and Brown (1980) bases on a similar principle but the proper Nyquist interval is determined by comparing each datum to an average of preceding velocity values in the radial. This local averaging helps to deal with incorrect or missing data.

The two methods mentioned are one-dimensional techniques since they aim at a good continuity by analyzing single radar beams. In many cases this will not be sufficient as strong natural shear zones cannot be distinguished from aliasing zones. The information from a second dimension helps to identify the artificial shear produced by folding.
2.2. Existing Doppler velocity dealiasing techniques

Two-dimensional techniques are generally less sensitive to missing data. Hence, more recently developed techniques call in additional radials or dealias the Doppler velocity image, i.e. a complete revolution of the radar antenna at one elevation angle. Such a method was proposed by Merritt (1984) using three steps. The first step segments the data into regions of similar velocities where all the velocities in each region are within some percentage of the Nyquist velocity of each other. Then the shears along the borders are minimized by determining the proper aliasing interval for each region. The third step uses a wind model to determine the proper aliasing interval of large areas, which should already be internally consistent.

A derivative of Merritt’s technique was developed by Boren et al. (1986) by adding a wind field model monitor. A simple set of rules is used to determine whether the wind field model is correct. If errors occur, the current model is abandoned and replaced with a preceding model that was considered valid. This eliminates propagation of errors that might occur in the wind field model, what was found to be an intermittent problem with the Merritt system. Bergen and Albers (1988) modified Merritt’s technique by adding a noise filter, a technique to deal with ground clutter, and the use of a sounding (rather than a wind field model) to estimate the dealiasing interval of distant echoes which do not have continuous velocity observations out to their range.

Eilts and Smith (1990) introduced a technique called local environment dealiasing (LED), which incorporates local information on the current ray as well as previous rays to improve the dealiasing decision. LED substantially improved a basic line expansion algorithm. With properly tuned algorithm parameters, their technique was applied to Doppler radar data used in the Terminal Doppler Weather Radar (TDWR) project with success, and is the algorithm presently used in the NEXRAD (Next Generation Weather Radar) system. Jing and Wiener (1993) proposed a method which attempts to dealias a connected two-dimensional region by minimizing all detected continuities caused by aliasing. The detection uses a conventional threshold method and the discontinuity minimization is performed by solving a least-square problem. This procedure is combined with a global dealiasing algorithm using environmental wind information.

One of the latest proposed dealiasing schemes was presented by Curtis and Houze (2001). Their method is four-dimensional, hence considers both all tilts from a volume scan and the previous scans as a reference. Six steps are performed for each tilt starting with thresholding and filtering of the input data. Gates are then compared to the previous value and the next higher elevation. Starting with the confident gates from the last step, neighbored values are corrected to achieve continuity. The last two steps dealias isolated gates by averaging the result from their vicinity and correct all remaining
gates with a VAD.

The variational dealiasing method presented in the following adopts some features of existing techniques, which are considered to be reliable and well developed. Objectives prosecuted when having initiated the work on a new algorithm were

- to dealias Doppler velocity images under different meteorological situations and data availability (within the image and concerning a background wind field),
- to be able to correct spatially isolated observations in the PPI,
- not to force overall continuity but to distinguish between zones of artificial and natural shear,
- to avoid the propagation of errors and
- to gain an estimate for the quality of each Nyquist number which is assigned to correct the observations.

2.3 Data Preparation

2.3.1 Noise removal

The dealiasing algorithm starts by reading the Doppler velocity PPI observations. In order to minimize the computing requirements, i.e. to accelerate the process, these images need to be filtered appropriately. Small echo fragments consisting of only a few gates or even a single gate, which are isolated from larger coherent echo regions by missing values, are supposed to be erased from the Doppler velocity image. In general, they will be of negligible meteorological value, and, if the distance to a coherent echo is large, they might even be difficult to be dealiased by the human eye. We adopt the three-step procedure of Bergen and Albers (1988) to pre-filter the Doppler velocity PPIs. The first step fills in gates with missing velocity where the adjacent velocities at either side (eight neighbors) are valid. The median value of the eight adjacent velocities is inserted. Hence, this step avoids isolated missing gates. The second step is a five-neighbor filter: if a gate contains a valid velocity value but is surrounded by fewer than five valid gates, it is replaced by a missing value indicator. The five-neighbor filter smoothes harsh echo boundaries and through this diminishes the number of echo regions (Section 2.3.2). The last step removes isolated gates, i.e. gates surrounded by eight missing values, resulting from the previous step. Bergen and Albers (1988) defend
this procedure because the computing time is economical and the velocity values are not altered. The latter point is of paramount importance: the observations are merely erased or replenished without altering finite values. The echo boundaries, not the echo values, are smoothed.

2.3.2 Segmentation

In analogy to what we do when dealiasing a Doppler velocity image with the help of our eyes, the algorithm identifies coherent regions of presumably equal Nyquist number by region growing (Wirth 1976). All missing values belong to a unique missing region (the only non-coherent region). A region is identified by starting at any point in the image and recursively expanding as far as the sign of the velocity does not switch. All gates found will belong to the same region. As a consequence a region contains only away or only towards velocities and is either bound with zero velocity or missing values, or with folding lines. The identification of regions is repeated with new starting points until a region is assigned to each gate.

Bergen and Albers (1988) and Jing and Wiener (1993) applied similar techniques to segment the Doppler velocity image but used a velocity shear criterion for bounding the region, not the change of sign of the velocity value. Their method will identify a larger region where a zero velocity line is present but is more consuming in terms of computing time. Both techniques can fail by erroneous welding of two regions which actually possess different Nyquist numbers. This effect is called bridging and is one major error source. Albeit the increased computing requirements, higher horizontal resolution reduces the risk of bridging. In the immediate vicinity of the antenna, the risk for bridging can be enhanced if working in Cartesian coordinates. An artificial data ‘hole’ around the antenna can help in this case. The radar image size and the number of identified regions are variables influencing the computing time of the algorithm.

2.3.3 Centroids

Each region found by the segmentation is marked with a centroid. Centroids are first located geometrically, i.e. by calculating the mean coordinates of its gate elements. Since the regions can be of arbitrary shape, it is further postulated that the centroids do not lie on (or outside) the very boundary of a region (if the region is large enough) and that the Doppler velocity at the centroid is around the average velocity of the region. This ensures the centroid to be an element of the region and can represent the region
appropriately for later calculations in the variational algorithm (Section 2.4.5). Figure 2.1 holds a sample Doppler velocity image with centroid marks inserted.

![Sample Doppler velocity image with centroid marks](image)

**Figure 2.1:** Sample Doppler velocity image with the region centroids marked with crosses. The triangle marks the position of the radar antenna.

### 2.3.4 Zero velocity and shear marks

For the variational formulation selected neighbored-gate pairs are marked. On the one hand we look for gates on the region boundaries 1) having a Doppler velocity of approximately zero and 2) being adjacent to a gate with approximately zero Doppler velocity from a different region. Gate pairs along zero velocity lines in the Doppler image are seized with these marks (Figure 2.2). Depending on the discretization of the radar data storage format, a threshold value for defining a zero velocity gate can be set. A more crucial point is that a clutter filter might erase a large amount of zero velocity gates. This effect was pointed out in Section 1.4 and handicaps the identification of a coherent zero velocity line.

On the other hand adjacent gate pairs are searched which belong to different regions, respectively, and over which there exists Doppler velocity shear of approximately twice the Nyquist velocity. These marks hold shear lines which are artificial (aliased) with high probability. There is a risk of detecting natural shear lines with this as well. This risk is enhanced the lower the Nyquist velocity is given. The thresholds for natural shear must be set accordingly. Figure 2.2 shows the marks found in a sample Doppler velocity image.
2.4 Variational formalism

2.4.1 The minimization of the cost function

The procedure to dealias the Doppler velocity image is based on a variational technique. Though taking the observations at single gates into account, the image is dealiased regionwise. A Nyquist number is to be assigned to each region identified in Section 2.3.2, with which the region can be corrected. The Nyquist numbers are determined by varying them systematically in a manner to match with a series of constraints we define. Hence, the Nyquist numbers are the so-called control variables for an objective analysis. The constraints are formulated such that they return a positive scalar value expressing the degree of adaption of the objective analysis. In order to achieve this they are formulated in a quadratic form. A value of zero denotes complete adaption. The sum of these constraints is called the cost function \( J \). We can systematically minimize the cost function - and with this better fulfill the constraints - by iteratively following the

Figure 2.2: Same Doppler velocity image as in Figure 2.1 with artificial shear and zero velocity points marked. Diamond symbols denote a zero velocity point, x-symbols the artificial shear points. The triangle at the center marks the position of the radar antenna.

With these to mark types different regions are set in relationship to each other. Regions sharing a zero velocity line are held to have equal Nyquist numbers. Regions sharing an artificial shear line are supposed to be shifted to smooth the discontinuity.
negative gradient of the cost function with respect to the control variables. This path will lead to the minimum of the cost function if an appropriate step length is selected. The step length should be large enough to allow a fast convergence rate but at the same time small enough in order not to pass the minimum. Laroche and Zawadzki (1994) explain the mathematical details to this problem. They further propose the use of the conjugate gradients $d_k$ for an improved descent algorithm (2.3). The termination criterion for the minimization can be set either by a minimum difference in $J$ between two iterations and/or by a maximum number of iterations.

$$
ge_k = \frac{\partial J}{\partial X} \quad (2.2)$$

$$d_k = -g_k + \frac{g_k^T g_k}{g_{k-1}^T g_{k-1}} d_{k-1} \quad (2.3)$$

$g_k$ is the common gradient, i.e., the derivation of the cost function $J$ with respect to the control variables $X$, $g_{k-1}$ its previously calculated correspondent.

Constraints can be formulated either in a strong or a weak manner. Strong constraints need to be fulfilled exactly. As a consequence they do not contribute to the cost function but influence the gradients with their adjoint (Sasaki 1970). We will not use any strong constraints for this dealiasing technique. Weak constraints allow for a residuum in the adaption of the objective analysis. Their weights can be steered with weight factors (Section 2.4.7). In general, weak constraints are applied where there remains a degree of uncertainty about a constraint or where the model is fitted to observations affected with a known error. The weight of the constraint is inversely proportional to this error. The following sections will define the constraints applicable to dealias the Doppler velocity image.

### 2.4.2 A constraint for zero velocity marks

Section 2.3.4 described the identification of zero velocity marks being locations (adjacent-gate pairs) in the Doppler velocity image where a zero velocity line is supposed. Since the region growing technique for the segmentation of the observations cannot pass a zero velocity line, a constraint is set tying the two regions sharing a zero velocity mark. This constraint is formulated in a way to force the Nyquist numbers $n$ of the two involved regions $r$ to be equal.
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\[ J_0 = \sum_z w_0 \left[ n(r_{z_1}) - n(r_{z_2}) \right]^2 \] (2.4)

\( J_0 \) is the contribution of the constraint for zero velocity marks to the cost function with weight \( w_0 \). \( z \) is an index for all zero velocity marks where \( z_1 \) signifies the first gate and \( z_2 \) the second gate of each gate pair.

2.4.3 A constraint for artificial shear marks

The identification of marks for artificial shear, i.e. shear produced by aliasing, was outlined in Section 2.3.4. They hold an adjacent gate pair over which there exists a gradient in the Doppler velocity image of approximately twice the Nyquist velocity. The following constraint pushes this discontinuity to vanish by adjusting the Nyquist numbers of the two involved regions.

\[ J_s = \sum_s w_s(s) \left[ (v_M(s_1) + 2n(r_{s_1})v_\alpha) - (v_M(s_2) + 2n(r_{s_2})v_\alpha) \right]^2 \] (2.5)

\( J_s \) is the contribution of the constraint for shear marks to the cost function with weight \( w_s \). \( s \) is an index for all shear marks where \( s_1 \) and \( s_2 \) identify the two elements of the gate pair, respectively. \( v_M(s_1) \) and \( v_M(s_2) \) are the observed velocities at these two gates.

2.4.4 A constraint for the environmental wind

The two constraints mentioned so far are themselves able to shift the regions and to produce an image without artificial discontinuities. However, there are multiple solutions feasible: the entire image can be shifted by \( 2iv_\alpha \), where \( i \) is an integer such that different wind velocities are possible. There are two ways to overcome this ambiguity.

1) One region needs to be determined which is already in the correct Nyquist interval. Unfortunately, this task is critical and a weakness of other techniques. Usually a region very close to the radar is chosen. During convective situation where the closest echo is very distant, or when multiple folding happens, a reliable automatic identification becomes impossible.

2) Information about the environmental wind, i.e. the mean horizontal wind field, is included in the analysis. The mean wind helps to establish the range or number of possible Nyquist intervals. The environmental wind field can origin from different sources,
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... e.g. from a numerical forecast model, from a radio sounding, or from alternative radar products as the VAD (velocity azimuth display) or a reflectivity tracking technique like COTREC (tracking of radar echoes, Li et al. (1995)). The first three will provide a vertical wind profile, whereas a tracking yields only one averaged height level. On the other hand, a tracking allows to resolve different flow regimes in the horizontal dimensions.

We intend to use the first method only in the case of an emergency when everything else fails. In general, some environmental wind product is available and consulted for the dealiasing. PPIs, which are the product to dealias, are taken at a distinct elevation, hence intersect the atmosphere at a height increasing with the distance from the antenna. For this reason the environmental wind at the corresponding height for each radar gate is considered if available (VAD) or appropriate (TREC). From this wind vector the radial wind component $v_{ew}$ is calculated to be set in relationship with the observed (and corrected) Doppler velocity $v_M$. The observation is expected to be in approximate agreement with the radial velocity simulated from the environmental wind. This is expressed as the third constraint in Figure 2.6.

$$J_{ew} = \sum_{i,j} w_{ew}(i, j) [v_M(i, j) + 2n(r(i, j)) - v_{ew}(i, j)]^2$$

(2.6)

$J_{ew}$ is the contribution of the environmental-wind constraint to the cost function with weight $w_{ew}$ for each gate at the coordinates $(i, j)$. $v_M$ is the measured Doppler velocity. $v_n$ is the Nyquist velocity and $n(r)$ the Nyquist number of each region $r(i, j)$. The quadratic difference between the observation and the value from the environmental wind is summed over all gates.

2.4.5 A constraint for distant isolated regions

It is feasible that for certain regions none of the above mentioned constraints applies. This is the case if a region is isolated and the environmental wind is not representative for this region (see Section 2.4.7). In order to determine the correct Nyquist number of these regions, we use the following additional weak constraint: The nearest neighbor region (of similar size) to the isolated region is searched by using the representation of the centroids. The Doppler velocity profile along the linear connection of the two centroids is compared to a linear interpolation (2.7) of the Doppler velocity between the two centroids (Figure 2.3). The quadratic sum of the differences between the two profiles yields the contribution of the constraint to the cost function. In (2.7) and (2.8), $d$ is the horizontal coordinate along the profile, $D$ the length of the profile and $v_1$ as well...
2.4. Variational formalism

as \( r_2 \) the indices of the two region centroids involved, respectively.

\[
v_i(d) = \left(1 - \frac{d}{D}\right)\left\{v_M(r_1) + 2n(r_1)v_a\right\} + \frac{d}{D}\left\{v_M(r_2) + 2n(r_2)v_a\right\}
\]  

(2.7)

\[
J_c = \sum_r w_c(r) \left[ \sum_{d=0}^D \left\{\left(\frac{v_M(d) + 2n(r_d)v_a}{v_i(d)}\right) - v_i(d)\right\}\right]^2
\]  

(2.8)

Figure 2.3: Solid lines show the measured Doppler velocity \( v_M \), the dashed line the correctly dealiased line. The circles mark the centroids which are connected with a linear interpolation of the Doppler velocity (dashed-dotted line). The area between the solid lines and the linear interpolation is the summed difference contributing to the cost function.

2.4.6 Verifying the gradient of the cost function

A consistent method to verify the mathematical implementation of the cost function and the constraint gradients is to compare the calculated gradient \( \frac{dJ}{dN} \) to the inclination of the cost function measured over a given step length (Laroche 1994). By decreasing the step length iteratively, the inclination must converge towards \( \frac{dJ}{dN} \). If not, an efficient convergence towards the minimum of the cost function is not guaranteed. This procedure is performed after every change to the algorithm code and helps to discover conceptual and technical errors. All experiments in this work are performed after this verification.
2.4.7 Constraint weighting

The definitions of the aforementioned constraints let suppose that for some regions the application of all four constraints lead to redundancy or even competition. E.g., it is not appropriate to use the constraint for distant isolated regions where the information from a VAD is reliable. Furthermore, the orders of magnitude of the different constraints span over several decimal powers. For these reasons the four constraints are weighted regionwise to contribute to the cost function in a balanced manner. In addition to this, the weight factors possess units which render each constraint unit-less. This is mathematically necessary to allow summing the single costs to the cost function $J$.

We first reflect under what conditions some constraints can be omitted. If the boundary conditions for the identification of artificial shear marks and zero velocity marks are well set, these marks are very reliable. Therefore, the according constraints are always applied. An exception arises when two regions are bound with both artificial shear marks and zero velocity marks. The two constraints would force opposing corrections. Where this happens, the zero velocity line constraint is omitted (weight equals zero) for the corresponding region pair, i.e., the artificial shear constraint is dominant.

The application of the constraint for the environmental wind strongly depends on the origin of the information and with this on its representativity. A VAD provides a vertical profile of the horizontal wind determined from a usually highly elevated PPI. Consequently it is primarily representative for the vicinity of the radar (e.g. <30 km) and not necessarily for the entire PPI range. For regions outside the representative range the constraint considering the environmental wind is weighted zero. The representativity from a radio sounding is given by the flight path. If the environmental wind origins from a radar echo tracking algorithm, the representativity depends on the resolution and position of the tracking boxes. Dangerous is the fact that, according to the PPI elevation, at far range echoes from higher altitude are tracked than at short range. When the wind shear is strong, the vertical gradient is mixed with the horizontal variation and the representativity suffers. Numerical models provide the wind field at the model's grid points. The type of the model will yield the risks involved: small scale structures might not be resolved and the model prediction can fail.

Regions identified by the segmentation of the Doppler velocity image are only affected by the constraint for the environmental wind where the environmental wind is considered representative. Regions beyond the representative areas but included in artificial shear and zero velocity marks are expected to be adjusted by these constraints. From this concept it follows that in a cluster of multiple regions - all tied with marks - it is sufficient if one of the regions considers the environmental wind information. The largest
region in the cluster is selected for this purpose by the algorithm, in which the best agreement with the environmental wind is expected.

Only if a region is neither involved in mark constraints nor in the environmental wind constraint, or an isolated cluster of regions is at none of the region centroids within the representative area of the environmental wind, we will apply the constraint for distant isolated regions. For all other regions this constraint is weighted zero.

Until now it was only discussed under what circumstances constraints are applied or omitted. The weights further need to be adjusted relative to each other. In order to estimate the order of magnitude of the constraints the significant terms in (2.4), (2.5), (2.6) and (2.8) are regarded in Table 2.1. For all constraints units are eliminated by dividing by unity.

Table 2.1: Order of magnitudes of the four constraints defined for the variational dealiasing.

<table>
<thead>
<tr>
<th>equation</th>
<th>significant terms</th>
<th>order of magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2.4)</td>
<td>[n(r_{z1}) - n(r_{z2})]^2</td>
<td>0.1</td>
</tr>
<tr>
<td>(2.5)</td>
<td>[(v_M(s_1) + 2n(r_{s_1})v_a) - (v_M(s_2) + 2n(r_{s_2})v_a)]^2</td>
<td>100</td>
</tr>
<tr>
<td>(2.6)</td>
<td>[v_M(i, j) + 2n(r(i, j)) - v_{ew}(i, j)]^2</td>
<td>100</td>
</tr>
<tr>
<td>(2.8)</td>
<td>[\sum_{d=0}^D {(v_M(d) + 2n(r_d)v_a) - v_r(d)}]^2</td>
<td>100</td>
</tr>
</tbody>
</table>

The weight of each constraint is to be inversely proportional to the order of magnitude indicated. Apart from the numbers in Table 2.1 it has to be considered that a region can be involved in several (approximately 1 to 100) artificial shear or zero velocity marks. The weight is supposed to grow with the number of marks albeit the weight of the constraint for the environmental wind simultaneously loses importance. The positive weight in the constraint for distant isolated regions is less important as this constraint is only set where no other constraint is applicable (and competing). Nevertheless, the weight factor is adjusted to contribute to the cost function with a sensible magnitude in order the criterion for terminating the minimization procedure not to be prematurely satisfied.

2.4.8 The integrity of the Nyquist numbers

The principles of a variational analysis require that the control variables (Section 2.4) are varied systematically (with the help of the conjugate gradient technique) yet at ar-
bitary small step lengths. The control variables in this study, however, are the Nyquist numbers of the regions in the Doppler velocity images and a Nyquist number, by its physical definition (Section 2.1), is an integer variable. The control variables are not expected to converge exactly to integer values. A hint for this was given by the exclusive definition of weak constraints. Especially while defining the constraint for the environmental wind we were allowing for some deviation from a mean wind, as at each pixel the wind is composed of a mean flow plus a local wind variation.

There are basically two ways to render the Nyquist number integer as it is required by definition. One the one hand we could introduce an additional constraint attracting the Nyquist numbers $n$ towards integer values. A possible implementation is given by (2.9).

$$J_{int} = \sin^2(n\pi)$$

(2.9)

$J_{int}$ possesses minima at all integer values $i$ and maxima at $i+1/2$. The problem accompanying this implementation is that it not only drives the Nyquist number to the correct value, but also inhibit the Nyquist number of leaving an incorrect value. Eventually, this hinders dealiasing.

Figure 2.4: The dealiasing product of the example used in Figures 2.1 and 2.2. The triangle marks the position of the radar antenna.

The second and in this study applied method is to minimize the cost function as described and afterwards round the Nyquist numbers. We can only expect this method to be reliable if the majority of the Nyquist numbers are close to integers. Nyquist numbers close to $i + 1/2$ are suspicious and incompatible with this algorithm’s model. The
2.5 Tests with a simulated PPI

The integrity of the calculated Nyquist number offers to be a quality estimate for the dealiasing of each region. For an ideal case unequivocal Nyquist numbers close to integer numbers are expected.

After minimizing the cost function, thus satisfying the constraints the best way possible, and after rounding the Nyquist numbers, the Doppler velocity image is dealiased by using (2.1) with the Nyquist number found for each region. The dealiasing product of the example used in Figures 2.1 and 2.2 is shown in Figure 2.4. The correction is well done and no dealiasing errors are visible. The corrected radial velocities indicate speeds up to approximately 30 m/s. In Section 2.5 we will check the proposed dealiasing algorithm with a simulated PPI for the consistency of the constraints. In Section 2.6 real radar data will be dealiased.

2.5 Tests with a simulated PPI

A simulated Doppler velocity PPI without clutter and erroneous measurements helps to test the dealiasing algorithm. In the first place we aim at investigating if the algorithm is indeed able to dealias the image correctly. Furthermore, the integrity of the resulting Nyquist numbers is an indicator for the correctness of the implementation and will be analyzed in the following.

From an analytic wind field with a uniform west wind of 20 m/s the radial velocities are calculated using the geometric relationship (3.2) and artificially aliased, i.e., velocities larger than an imaginary Nyquist velocity of 16 m/s are folded into the Nyquist interval. Figure 2.5 shows the simulated Doppler velocity PPI. The image is separated into three internally coherent areas by two lines of missing values. Doing this, the treatment of isolated regions can be studied.

The filters outlined in Section 2.3.1 are redundant for the simulated PPI, as no noise is simulated. The segmentation identifies the eleven regions simulated, also shown in Figure 2.5 with the region numbers. The artificial shear and zero velocity marks found by the algorithm are inserted into the Doppler velocity image in Figure 2.6 (for a better view only every fourth mark is plotted). These marks lie on the very boundary of the regions. Discontinuities over them will be forced to vanish with the help of the constraints. Note that the isolated areas in the NW and SE corner (regions 2, 3, 5, 8 and 11) are tied to clusters with marks, however, not in relationship to the large area around the radar antenna with the marks.

It was described in Section 2.4.7 that the constraints defined for the variational dealias-
Chapter 2. Variational Dealiasing

Figure 2.5: The simulated PPI of Doppler velocity is depicted. A uniform west wind of 20 m/s is assumed and artificially folded into a Nyquist window with $v_n = 16$ m/s. The white lines with missing values separate three major areas. The centroids of the regions found by the segmentation procedure are numbered in the figure.

Figure 2.6: The same simulated Doppler velocity PPI as in Figure 2.5 is shown, but the artificial shear marks and zero velocity marks are added to the figure.

The algorithm can be separately applied or omitted by varying their weight. However, it is not conceivable to apply the constraint for the zero velocity line and the constraint for artificial shear on their own, since they correct the regions in the Doppler velocity image relative to each other, but cannot give the 'absolute' wind. Either the constraint for some environmental wind needs to be added or a region needs to be guessed una-
liased. Depending on whether the environmental wind can be assumed representative for the entire PPI or not, the constraint connecting isolated regions may be necessary. I.e., if for instance a VAD/VVP is assumed representative for a radius of 20 km around the antenna, isolated regions beyond this radius need to be 'connected' to the closer regions with the constraint in Section 2.4.5. We test the dealiasing method first assuming an environmental wind representative for the entire PPI, omitting the constraint for distant isolated regions. In a second step a VAD indicating the wind close to the antenna is simulated, thus isolated regions 2, 3, 5, 8 and 11 are influenced by the respective constraint from Section 2.4.5.

2.5.1 No constraint for distant isolated regions

Assuming a uniform westerly environmental wind of \((u,v)=(20,0)\) m/s, which shall be representative for the entire PPI, the constraint for distant isolated regions can be omitted. This idealized case is rendered more meaningful by restricting the constraint for the environmental wind to observations close to the radar (<20 km) and the largest regions in isolated clusters. Doing this, the dealiasing algorithm will be forced to adjust all other regions merely with the mark constraints. Figure 2.7 shows which Doppler velocity pixels are affected by the constraint for the environmental wind. The goal of this weighting is to as to say 'nail' one representative (large) region in each coherent region cluster and to avoid 'loose' clusters whose regions are only adjusted internally relative to each other.

The minimization of the cost function can be started after weighting the constraints and analyzed by viewing the costs of each constraint along the iteration. Figure 2.8 indicates that the constraint weights are well balanced, though the constraint for the zero velocity can be fulfilled more efficiently.

Figure 2.9 shows that the final dealiasing product is correct. Four regions have been assigned a non-zero Nyquist number. However, in order to judge the validity of the algorithm, the calculated Nyquist numbers need to be scrutinized as they are output from the variational analysis, i.e., not the rounded values. Figure 2.10 shows a histogram for the adjusted Nyquist numbers of the regions in the Doppler velocity image. The histogram elements are shaded to indicate the size of the regions they represent. This allows to identify the large regions (dark shades) what will be more important in the later use of this figure type. Figure 2.10 reveals that the variational analysis pushes the Nyquist numbers towards the correct integer values. This demonstrates that the algorithm is viable and the first three constraints are correctly implemented.
Figure 2.7: Shaded areas indicate where the constraints for the environmental wind and for distant isolated regions are acting. In the lightly shaded area around the antenna the environmental wind is considered. The darker areas are either constrained for distant isolated regions (Section 2.5.2) or with the environmental wind (Section 2.5.1). The idea is to have no ‘loose’ region clusters in the image.

2.5.2 Adding the constraint for distant isolated regions

In contrast to the experiment in Section 2.5.1 the environmental wind information is assumed representative only for a radius of <20 km. This is comparable to the VAD or VVP product from a highly elevated weather radar scan. Under these circumstances and using the identical simulated PPI as in Section 2.5.1, the constraint for the environmental wind is applied merely in the light-shaded area in Figure 2.7. The isolated regions are influenced by the respective constraint described in Section 2.4.5, again only for the largest region in each cluster. They are indicated with the dark-shaded areas in Figure 2.7.

Repeating the dealiasing with the new weights and the constraint for isolated regions inserted, the minimization happens as visualized in Figure 2.11. The CIR starts contributing to the total cost after a delay of one iteration and thereafter adjusts the isolated regions 2, 3, 5, 8 and 11 to a continuous Doppler velocity image. The calculated Nyquist numbers are plotted in the histogram in Figure 2.12. Comparing the histogram to the analog Figure 2.10 for the experiments without the CIR, we note a smearing of the Nyquist numbers around the integer values. Nevertheless, the separation and orientation towards the integers is obvious and unambiguous. The origin of the smearing is that the CIR assumes a linear progression in the Doppler velocities between the region of interest and its/their nearest-neighbor region(s). This linearity is only an approxima-
2.5. Tests with a simulated PPI

Figure 2.8: The cost of each constraint during the minimization procedure, scaled with the iteration number on the x-axis. The experiment for the simulated PPI without using the constraint for distant isolated regions is shown. EWC abbreviates environmental wind constraint, ZVC the zero velocity line constraint, ASC the artificial shear constraint and CIR the constraint for the distant isolated regions.

Figure 2.9: The dealiasing product of the simulated PPI shown in Figure 2.5 and 2.6. The connection which is in fact on a conical PPI surface. The constraint cannot be satisfied arbitrarily well thus causing a slight shift off the integer values. We can expect to encounter similar smearing in all observational data as shown in the subsequent examples and Chapter 4. After rounding the Nyquist numbers of this experiment, the identical correctly dealiased Doppler velocity image as in Figure 2.9 is provided.
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Figure 2.10: Histogram of the region Nyquist numbers determined with the dealiasing algorithm for the simulated PPI experiment without the constraint for distant isolated regions.

Figure 2.11: Same as Figure 2.8 but for the experiment adding the constraint for distant isolated regions CIR.

2.6 Tests with a real Doppler velocity PPI

The simulated PPI from Section 2.5 offers almost ideal conditions to the dealiasing algorithm. No noise is simulated and the wind is uniformly from the west, such that the environmental wind constraint is appropriate at each pixel and all marks are reliably set. In real Doppler velocity observations clutter, statistical variations of the radar measurements and the inhomogeneity of the wind field do not guarantee that the constraints can be satisfied exactly. This was already anticipated by the definition of weak constraints in Section 2.4 and reflected in the calculated Nyquist numbers as they are determined
2.6. Tests with a real Doppler velocity PPI

Figure 2.12: Same as Figure 2.10 but for the experiment applying the constraint for distant isolated regions CIR. with the variational algorithm (before the rounding). In this section the behavior of the dealiasing algorithm for real PPI samples is investigated.

2.6.1 Case study with a winter snowfall

Figure 2.13: Lightly shaded areas show gates considered by the environmental wind constraint for the sample PPI from 17 February 1999. Darker shades indicate regions which are adjusted by the constraint for isolated regions.

The first sample PPI was used for outlining the constraints in Sections 2.3.2 to 2.4.8. The Doppler velocity PPI together with the identified centroids and marks is depicted in
Figures 2.1 and 2.2. It was scanned during a winter snowfall on 17 February 1999 and can be classified as stratiform precipitation. Since a VVP from the ETH radar served as the environmental wind guess for the sample PPI, Figure 2.13 shows that merely gates in the vicinity of the radar are considered by the respective constraint. Furthermore, only a few isolated regions need to be adjusted by the constraint for isolated regions, because the Doppler velocity image is widely coherent.

![Graph showing the development of costs](image)

Figure 2.14: Same depiction of the minimization of the costs as in Figure 2.8 for the sample PPI from 17 February 1999.

![Histogram showing Nyquist number](image)

Figure 2.15: Same as Figure 2.10, but for the case study of a winter snowfall.

Figure 2.14 shows the development of the costs of each constraint during the minimization. All constraints are practically minimized within a few tens of iterations. The Nyquist number histogram in Figure 2.15 shows the same information as Figure 2.10.
The shade of gray of each histogram element qualitatively indicates the size of the region (dark shade indicates a large region). The peaks at integer numbers indicate that the regions in the Doppler velocity image are reliably dealiased in general. We further note that primarily the large regions occupy places at integer numbers, whereas small regions cause the width (or smearing) of the peaks. This indicates a more reliable dealiasing of the large regions being a paramount advantage for the application since regions with ambiguous calculated Nyquist numbers might be filtered out (Section 2.7). The reason for which large regions’ Nyquist numbers are closer to integer values are two-fold:

- Large regions have more weight in the determination of the environmental wind as far as the latter origins from the same radar image. If from a VAD or VVP, a great part of the gates to which the VAD model is fitted to belong to the large regions. If a reflectivity tracking is performed with a correlation technique, the shifting of the large regions dominates the result. Small regions might be merged to the large regions, since only the reflectivity is considered in the tracking. In both cases, the constraint for the environmental wind matches better with the large regions.

- Within large regions there exists a distinct continuity and better resolution in the Doppler velocity structure which extends to the region boundaries. As a consequence, the region boundaries are well represented in shape and in quantity. The zero velocity constraint and the artificial shear constraint profit from this and can be better satisfied. Small regions can be dominated by inhomogeneities of the wind field.

The regions in the histogram in Figure 2.12 which own calculated Nyquist numbers around -0.5 and 0.5 are relatively small. There, the algorithm was not able to ‘decide’ which of the two bounding Nyquist numbers is the correct one, though the rounding would assign the nearest integer values to them. These regions need to be considered suspicious. Checking the positions of the seven suspicious regions in the example reveals that all of them are in SE sector of the image, i.e. in the sector affected by clutter from the Swiss Alps.

### 2.6.2 Case study with a convective summer situation

In order to scrutinize the behavior of the dealiasing algorithm in a convective storm situation, a PPI from 31 May 2001 0654 UTC is dealiased. In contrast to the example in
the last section, the echo structure is very incoherent, i.e., relatively small isolated cells
cast an echo onto the radar image. Figure 2.16 shows the observed Doppler velocity
after the filters from Section 2.3.1 have been applied. We recite to show the centroids
as well as the shear and zero velocity marks in a plot, since they were correctly detected
by the algorithm as expected.

Figure 2.16: The filtered Doppler velocity PPI scanned during a sample convective
storm situation.

A reflectivity tracking from ETH radar PPI scans supplies information about the environ-
mental wind. It is assumed representative for the entire PPI range, hence the constraint
for isolated distant regions is not applied in this example. The development of the cost
function contributions during the minimization is visualized in the left plot in Figure 2.17.
The role of the environmental wind constraint in a convective situation is dominant. Only
few zero velocity and shear marks are present because of the cell structure of the PPI,
hence, the corresponding constraints have merely influence on a few regions. Note that
a close-up on a single cell at high resolution would reveal valuable information about the
internal structure of the cell. Assuming a supercell, great wind shear and convergence
effects are expected as a part of the dynamics of the storm. This high resolution is
not used in this example, however, Chapter 4 will zoom into a rainband of an intensive
storm and study its internal structure.

Regarding the histogram on the right side in Figure 2.17 only few regions with sus-
picious calculated Nyquist numbers are notable. Especially the large regions are un-
ambiguously dealiased. The regions which the critical Nyquist numbers belong to are
located almost exclusively at the eastern end of the plot range. They cover an area
2.6. Tests with a real Doppler velocity PPI

Figure 2.17: Left plot: The development of the cost function and its contributors for the convective PPI example (for explanations see Figure 2.8). Right plot: Same histogram type as in Figure 2.15 for the convective sample PPI. Only a few regions are not conform with the objective analysis.

of 30 x 15 km and are eye-catching in a color view of the dealiased Doppler velocity image (Figure 2.18). The error just mentioned is too small to be visible in a grayscale plot. The suspicious regions do not harmonize with neighbored values and the environmental wind, and do not share marks with other regions. The question how to treat such regions will be answered in the following section.

Figure 2.18: Product of the dealiasing example during a convective summer situation. The picture is correctly dealiased except for small regions (see text) around the coordinate 790/215 (hardly notable in a grayscale plot).
2.7 A quality estimate for the dealiasing

A problem which is often encountered in dealiasing algorithms is that the success and quality of a dealiasing are difficult to analyze automatically and immediately after the procedure. However, if the corrected Doppler velocity data are to be further processed to any kind of wind product, dealiasing errors can be capital. Assuming a Nyquist velocity of e.g. 16 m/s, an untruly assigned Nyquist number can cause an error in wind velocity of 32 m/s. A quality control is of paramount importance.

In Section 2.6 it was found that the calculated value of the Nyquist number for each region informs about the unambiguousness of the assignment. A truncated value in the vicinity of 0.5 is suspicious, one close to an integer value signifies an unambiguous assignment of a Nyquist number to a region. This allows to introduce a quality estimate for the dealiasing of each region with the help of the truncated calculated Nyquist number. In an operational, automated environment, suspicious regions are rather erased than processed any further. The loss of Doppler velocity information in these regions is a drawback, however, dealiasing errors would be capital. For research purposes of a Doppler velocity image the interaction of a human operator can be required. In the current implementation of the dealiasing algorithm for the operational test platform (Chapter 6) all regions in the Doppler velocity image which have been assigned a calculated Nyquist number with a truncated value between 0.25 and 0.75 are marked suspicious, erased from the image and not further processed for the wind product.

2.8 Conclusions

The new variational dealiasing technique proves to be viable and applicable. A simulated PPI and radar observations during different meteorological situations are well corrected to provide the radial velocity information. The advantages of the presented variational dealiasing technique are the following:

- Under normal circumstances, no gates in the Doppler velocity image need to be assumed unfolded preliminarily. Abnormal circumstances would mean that no information about the environmental wind is available. Only if neither a VAD/VVP is available nor a pattern tracking (TREC) yields a reliable environmental wind estimate, nor a numerical forecast model or radiosounding provide a background wind field, the latter apply. Taking a previously derived wind field is an alternative background field then.
2.8. Conclusions

- The constraint for distant isolated regions allows to correct isolated observations where other constraints fail.

- Due to the constraint considering the environmental wind, the propagation of dealiasing errors is hindered. This renders the algorithm robust.

- By means of the calculated Nyquist number, a quality estimate for each region is available. Suspicious gates can be filtered with the consequence that no wind information remains at these spots.

- The variational analysis formulation allows for expanding the dealiasing technique in the future through the formulation of new constraints.

A weakness of the dealiasing technique can be located in the region identification (Section 2.3.2). If the wind field varies strongly in space and the spatial resolution of the PPI is coarse, a risk for bridging exists. In this case two gates are connected by the segmentation though they have different Nyquist numbers. Because both gates draw the Nyquist number in opposite directions, a truncated Nyquist number of approximately 0.5 is expected to be assigned. Hence, the bridged regions are expected to be filtered by the quality control (Section 2.7).

The dealiasing technique, as it is presented here, is implemented for research and operational application. It is currently tested as an IDL (interactive data language) code on archived and real-time observations. Because IDL is an interpreter (not a compiler) from a technical standpoint, it can correct the PPIs relatively slowly, but allows for comfortable debugging and analyses. Implementing the same technique in the Fortran or C language could improve the computing time by a factor of five to ten (personal estimation). Currently, the computing time in IDL is larger than the time to scan a PPI, hence operational application is merely feasible for a selection of PPI scans.

The experience with the algorithm shows promising results in different meteorological situations. A critical point is the decision, which environmental wind estimate is to be considered. The reflectivity tracking (TREC) can e.g. be used when the correlation coefficient exceeds a threshold value. The VAD/VVP itself provides a quality estimate but is often noisy. Chapter 6 will compile more thoughts about this.

Future development and experiments will aim at taking advantage of the third (spatial) dimension, when volume scans are available. This could result in a method dealiasing the highly elevated PPI scans first (minimal clutter) and use this information to correct lower elevations. This procedure might be worthful because the steep elevations are often corrected with less expense and higher reliability.
Chapter 3

Noise Filtering in a Variational Wind Field Retrieval from Doppler Radar

This chapter is a reproduction of the article


The layout of the article as well as the section, figure and table numbering were adapted to match with the thesis structure.

3.1 Introduction

Doppler radars enrich the meteorological observations by adding information about the velocity. This velocity describes merely the radial wind component. The two unknown components of the wind vector must be retrieved either with additional radars or by applying model assumptions about the wind field to the data. Several techniques for the retrieval of the wind field from radar data have been developed in the past: The velocity azimuth display (VAD) technique (Lhermitte and Atlas 1961, Browning and Wexler 1968) and the volume velocity processing (VVP) technique (Easterbrook 1975, Waldteufel and Corbin 1979) retrieve the mean vertical wind profiles from a single-Doppler radar. More rigorous models combine the Doppler radar observations with physical constraints and allow for the retrieval of the two- or three-dimensional wind field (Tuttle and Foote 1990, Sun et al. 1991, Qiu and Xu 1992, Xu et al. 1994, Laroche and Zawadzki 1994). The present study investigates noise filtering within the wind field retrieval algorithm of Protat and Zawadzki (1999). This algorithm is the multiple-Doppler
extension based upon the variational single-Doppler method of Laroche and Zawadzki (1994) and summarized in Section 3.2.

Weather radar observations — as any other measurement — are affected by errors from different sources. Echoes from side-lobes and ground clutter might be the most common elements of contamination by non-meteorological signals. In complex terrain with distinct topography these artifacts are more frequent. Airplanes, birds and insects are other targets meteorologists do not want to see on the radar display. Thus, depending on the application, radar data are filtered by the appropriate technique.

A retrieval of the wind field is often used for operational purposes and for the initialization of numerical forecast models. For these applications a representative and smooth wind field is required. Hence, noise filtering plays an important role in the retrieval process. Two noise filtering techniques are proposed by Protat and Zawadzki (1999): a data smoothing prior to the data assimilation and a smoothness constraint as part of the model. Their effect on the quality and performance of the wind field retrieval is studied in this paper. We summarize the wind retrieval technique, outline the noise filtering concepts and present the experiments. First experiments investigate the two-dimensional case, i.e. retrievals of the wind field without considering the vertical velocity. Section 3.5 expands to the three-dimensional case and explains implications for the vertical velocity.

### 3.2 Wind field retrieval

#### 3.2.1 Basics

Three-dimensional wind fields can be retrieved from the observations of one or several Doppler radars. Laroche and Zawadzki (1994) developed a variational analysis technique for a single Doppler radar. An extension for the use with multiple radar data is presented by Protat and Zawadzki (1999). The variational method minimizes the difference between the measured variables, i.e. reflectivity and radial velocity, and the objective analysis, i.e. predictions of a set of model equations.

The model equations can be formulated as weak or as strong constraints (Sasaki 1970). Constraints are formulated weak whenever a residual uncertainty for the underlying model assumption or law is allowed for. Weak constraints contribute to the cost function \( J \) being a measure for the degree of adaptation of the model wind field to the data. A scalar weight factor controls the contribution to the cost function. The weight
3.2. Wind field retrieval

is proportional to the inverse value of the expected model (constraint) error. In order to minimize the cost function conjugate gradients with respect to the control variables are used. Strong constraints need to be fulfilled exactly (zero contribution to the cost function), but influence the gradients of the cost function by their adjoint (Sasaki 1970). The inverse problem is to use the observations of reflectivity and Doppler velocity \( v_r \) and the constraining model to retrieve the unknown three-dimensional wind field. Since weak and strong constraints are mixed in this method, it is called a semiadjoint method by Laroche and Zawadzki (1994).

The wind field retrieval algorithm starts by reading CAPPI (constant-altitude PPI) data from all available radars. These raw data can then be filtered by what will be called a data smoothing in this study. The data smoothing method is described in Section 3.3.1. The control variables are initialized either by a zero velocity wind field in the case of a multiple-Doppler radar wind retrieval, or by a first guess being important for the single-Doppler radar method. The first guess usually origins from a VAD or a tracking algorithm (TREC).

After these steps the variables are ready for the minimization process. The next paragraphs list the model equations constraining the two-dimensional retrieval of the horizontal wind components \( (w = 0) \) in a dual-Doppler configuration. Constraints for the vertical velocity will be added in Section 3.5.

3.2.2 Radial velocity constraint

The radial velocity constraint is a weak constraint adjusting the model wind field to be consistent with the measured Doppler velocities of the radar(s). Its contribution to the cost function \( J_r \) - a measure for the closeness with which the objective analysis fits the observations - is given by (3.1) and (3.2), where \( N \) is the number of control variables and \( v_r \) is the radial velocity given by the model’s Cartesian wind components \( (u, v, w) \). \( \phi \) and \( \theta \) are the azimuth and elevation angles of a grid point relative to the radar, \( \vec{z}_r \) is the radial velocity observed by the radar and \( v_t \) the terminal fall speed of the precipitation (Section 3.5.2).

\[
J_r = W_r \sum_{n=0}^{N} (v_{rn} - \hat{v}_{rn})^2
\]  

(3.1)

\[
v_r = u \cdot \cos(\phi)\cos(\theta) + v \cdot \sin(\phi)\sin(\theta) + (w + v_t)\sin(\theta)
\]  

(3.2)
The weight $W_i$ is determined from the observational error, usually around 1 m/s for scanning radars. Note that for non-horizontal radar scans $v_r$ is also a function of the vertical wind component and the fall velocity of precipitation particles.

### 3.2.3 Smoothness constraint

Since the wind field retrieval deals with observational radar data, erroneous measurements and artifacts can sneak into the retrieval and yield unreliable wind vectors. In order to retrieve a smooth wind field, as it is required by assimilating models, Thacker (1988) suggested to add a smoothness constraint to the cost function. Mathematically the smoothness constraint is known as a penalty function (Daley 1991) in its general form

$$J_s(f_A) = \gamma \sum_{n=0}^{N} \left[ \frac{\partial^p}{\partial x^p} f_A(x) \right]^2$$

(3.3)

where $f_A$ is the objective analysis and $p$ controls the spectrum of $f_A$. $\gamma$ controls the trade-off between the penalty function and the other constraints. The smoothness constraint is through its definition implemented as a weak constraint. Section 3.3.1 will go into further details about the application of the smoothness constraint in this study.

### 3.2.4 The cost function

The cost function is the sum of the contributions by the weak constraints ($J = J_r + J_s$). The aim is to minimize the cost function for the best possible adaptation of the model predictions to the observations of the radar(s). The minimization is carried out by a conjugate gradient technique optimized for this purpose by Laroche and Zawadzki (1994). The adjoint technique (Sasaki 1970) prescribes that strong constraints as the continuity equation (Section 3.5.3) contribute to the gradient $\partial J / \partial \phi$ (where $\phi$ is a control variable) by the gradient with respect to the initial condition. The minimization (iteration) is pursued until a truncation condition is reached, usually a lower limit for the gradient's amplitude.
3.2.5 The numerical grid

The wind field retrieval algorithm uses a coordinate system as e.g. known from the MC2 grid (Desgagne et al. 1994). The radar data - reflectivity and Doppler velocity - are transformed onto a Cartesian grid. Those grid points are named q-points and positioned at the height of the grid momentum levels. The objective analysis is bound to a staggered grid as follows: the $u$- and $v$-components are horizontally staggered in the direction of their unit vectors, the vertical velocity grid is vertically staggered yielding the thermodynamic levels (Figure 3.1). The numerical benefit of this coordinate system is that the positions of the $u$- and $v$-points allow to calculate the divergence at the q-points. For the integration of the continuity equation (Section 3.5.3) this provides an ideal alignment of the variables. The grid resolution used in this study is 500 m horizontally and 1000 m in the vertical direction.

Figure 3.1: The numerical grid used for the wind field retrieval. The radar data are assumed to be on momentum levels at the q-points, the model wind components on a staggered grid at equal height levels. The vertical velocities are calculated on thermodynamic height levels without a horizontal staggering. Note that the lowest level is a thermodynamic level.
Chapter 3. Noise Filtering

3.3 Noise filtering

3.3.1 Filtering Techniques

Because of the expected error of Doppler velocity measurements, contaminations from ground clutter and other artifacts, some kind of noise filtering is indispensable for a successful retrieval of the wind field. The retrieval algorithm used in this work considers two different noise filtering techniques that can be applied in combination or independently from each other.

The first approach is a data smoothing applied to the raw radar data. For each data point a sphere of influence bounds the neighbors to be included for the filtering. The weighted average in the sphere of influence yields the filtered value. The weight \( w_s \) decreases exponentially off the center of the sphere as given by (3.4).

\[
w_s = ce^{-\frac{r}{r_{inf}}}
\]  

(3.4)

c is a constant, \( r \) the distance of a neighbored grid point, and \( r_{inf} \) is the radius of influence responsible for the weight's fall-off rate. A maximum radius is given as a further parameter \( r_{max} \). We define three strength levels for the data smoothing by the two parameters \( r_{inf} \) and \( r_{max} \), shown in Table 3.1. Stronger data smoothing did not proof to be reasonable as it leads to disappearance of the wind maxima.

<table>
<thead>
<tr>
<th>level</th>
<th>( r_{inf} )</th>
<th>( r_{max} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>weak (WDS)</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>medium (MDS)</td>
<td>1.0</td>
<td>2</td>
</tr>
<tr>
<td>strong (SDS)</td>
<td>2.0</td>
<td>4</td>
</tr>
</tbody>
</table>

The smoothness constraint, the second noise filtering approach, was pointed out in Section 3.2.3. Duchon (1976) and Wahba and Wendelberger (1980) adapted the penalty function for the two-dimensional case using \( p = 2 \) (3.5). This minimizes the curvature of the objective analysis or, in other words, tends to linearize locally the control variables \((u, v)\).
3.3. Noise filtering

\[
J_s = \gamma \sum_{n=0}^{N} \left( \frac{\partial^2 u}{\partial x^2} \right)^2 + 2 \left( \frac{\partial^2 u}{\partial x \partial y} \right)^2 + \left( \frac{\partial^2 u}{\partial y^2} \right)^2 \\
+ \left( \frac{\partial^2 v}{\partial x^2} \right)^2 + 2 \left( \frac{\partial^2 v}{\partial x \partial y} \right)^2 + \left( \frac{\partial^2 v}{\partial y^2} \right)^2 \right)
\] (3.5)

3.3.2 General remarks

Radar observations are usually subject to a number of filters, e.g. the clutter filter, in the processing of early radar products. These filters can erase observations from the radar image but should not alter the finite value of the observation. An exception are dealiasing techniques to correct folding at the Nyquist velocity. They shift folded Doppler velocity values by multiples of the Nyquist velocity and are a crucial step in the processing of Doppler velocities. Here we assume dealiased Doppler velocities.

We separate the data smoothing used here from the filters of a radar computer’s pre-processing. The latter will basically erase or maintain an observation. The data smoothing alters/edits the value of the observations in coherent regions of observations. The filtering is purely mathematical with no physical or meteorological background. We expect an efficient filtering especially where single data points appear as outliers of the surrounding field.

The smoothness constraint differs in its concept: whereas the data smoothing acts once, prior to the data assimilation, the smoothness constraint does not affect the observations but forces the objective analysis to be smooth. It accompanies the model wind field throughout the data assimilation and contributes to the cost function. With strength given by its weight factor \( \gamma \) the smoothness constraint competes with the other weak constraints and inhibits the model wind field to follow artifacts in the observations.

The noise examined in this study is random and Gaussian-distributed. None of the methods will be effective against spatially correlated noise. Biases can only be minimized by additional constraints to the model or observations presuming a good knowledge of the error structure of the radar observations. The smoothness constraint can, however, propagate reliable information into regions where only bad or unreliable measurements are available - a properly set weight is then necessary (Wüst et al. 1999, Guillemette and Zawadzki 1999).
Chapter 3. Noise Filtering

3.4 Experiments in two dimensions

3.4.1 The analytic wind field

Analytic wind fields are retrieved from simulated Doppler velocities to compare the effects of the two noise filtering techniques. Both a divergent and a rotating analytic wind field are chosen for representativity. The divergent, non-rotating wind field is given by (3.6) to (3.8). The divergence induces significant vertical velocities. The horizontal wind field at a height of 1 km is plotted in Figure 3.2.

\[
\begin{align*}
  u &= A \left( \frac{1}{2} - k z \right) \sin \left( \frac{2\pi x}{\lambda} \right) \\
  v &= A \left( \frac{1}{2} - k z \right) \cos \left( \frac{2\pi y}{\lambda} \right) \\
  w &= -\frac{4\pi}{\lambda k} \left( 1 + 2k z - \epsilon^k z \right) \left( \cos \left( \frac{2\pi x}{\lambda} \right) - \sin \left( \frac{2\pi y}{\lambda} \right) \right)
\end{align*}
\]

Figure 3.2: The divergent, analytic horizontal wind field in the retrieval domain at the height of 1 km (A=20 m/s).

\( u, v \) and \( w \) are the three Cartesian wind components. \( A \) is a constant for the amplitude of the wind field. \( z \) is the height of a grid level, \( k = 1/H \) a parameter for the reference
height $H$, and $\lambda$ determines the horizontal wavelength of the airflow. The rotating, non-divergent wind field is determined by (3.9) to (3.11). The vertical velocity is zero everywhere. The horizontal wind field at a height of 1 km is plotted in Figure 3.3.

$$u = -A \left( \frac{1}{2} - kz \right) \sin \left( \frac{2\pi x}{\lambda} \right) \cos \left( \frac{2\pi y}{\lambda} \right)$$  \hspace{1cm} (3.9)$$
$$v = A \left( \frac{1}{2} - kz \right) \cos \left( \frac{2\pi x}{\lambda} \right) \sin \left( \frac{2\pi y}{\lambda} \right)$$  \hspace{1cm} (3.10)$$
$$w = 0$$  \hspace{1cm} (3.11)$$

Figure 3.3: The rotational, analytic horizontal wind field in the retrieval domain at the height of 1 km ($A=20$ m/s).

Both wind fields satisfy the anelastic continuity equation (3.14) which is a requirement for a good retrieval of the vertical velocity. For the following experiments, $L=15$ km and $H=8$ km. $A$ is 5, 10 or 20 m/s depending on the experiment. With those wind fields and parameters we expect to represent a series of meteorological situations. Note that those equations only describe the variations of the wind field. A mean constant horizontal flow ($u_0, v_0$) could be added, to which all experiments are insensitive.
3.4.2 Methods

In order to simulate wind field retrievals from radar data, the velocity components radial to the radar positions are calculated from geometric relationships (3.2) and serve as input for the retrieval. Since the analytic wind field is smooth - except for discretization effects - artificial noise is added to the simulated radial velocities. The noise is generated randomly from Gaussian distribution with a standard deviation of 1 m/s. The impact of this noise on the simulated Doppler velocities is demonstrated in Figure 3.4. For a proper comparison of the retrieved wind fields, the random noise was generated once and reused for all experiments.

Figure 3.4: The impact of the artificial noise on the simulated radial velocities. For this example the divergent wind field with $A=5$ m/s at a height of 500 m is chosen.

For the given objectives retrievals of the wind field are run using one of the noise filtering techniques or both simultaneously. First we examine two-dimensional wind retrievals, i.e., the retrieval domain is at the height of the radar antennae (1 km a.s.l.). We use a domain (Figure 3.5) of 15 x 15 km horizontal size at 500 m resolution. The positions of the radars are such that each point in the retrieval domain projects an appropriate viewing angle (larger than 30°) towards the two radars.

The experiments are carried out with the divergent and the rotational wind field. A first control run is carried out without adding noise to the radial velocities and without using any noise filtering. In a second run the noise is added but, again, the wind is retrieved
3.4. Experiments in two dimensions

Figure 3.5: The horizontal position domain (solid square) wherein wind field retrievals are carried out. The domain is placed within the dual-Doppler region (dashed circles) of the two radars (triangles).

without a noise filtering technique. This run should give the worst case scenario. The data smoothing and the smoothness constraint are applied separately and combined.

In order to judge in what manner the retrieved wind field is affected by the different noise filtering techniques, we examine the following criteria:

- The *power spectra* are computed by a one-dimensional FFT (fast Fourier transformation) from the West-to-East horizontal wind components ($u$). These spectra are calculated in the entire wind retrieval domain, i.e., at 30 levels along the y-axis, and averaged to one spectrum per experiment. The power spectra indicate the efficiency of a noise filtering technique. Since the analytic horizontal wind field is sinusoidal, the ideal power spectrum is a delta function with the peak at a wavelength of $L=15$ km. The discretization will induce minor power for higher frequencies. Hence, a retrieval of the wind field without noise does not exactly reflect the analytic power spectrum.

- The *root mean square differences* (RMSD) between the retrieved wind components and the simulation are an appropriate measure to analyze the closeness of a retrieved wind component to the analytic one. The RMSD is defined as in (3.12).
where $N$ is the number of elements for the analysis, $x_i$ a retrieved wind component and $\tilde{x}_i$ the analytic value.

- The number of iterations of the wind field retrieval indicates how fast the retrieval algorithm converges towards the minimum of the cost function. It is a measure for the performance - in terms of computing time - of the wind field retrieval. Since the run-time of the algorithm on a modern workstation is comparable to the duration of a radar’s scan cycle this measure is important for operational purposes. The retrievals of the wind field are stopped after 500 iterations in any case.

### 3.4.3 Results

The power spectra for the two-dimensional experiments all have similar characteristics. To study two examples, Figure 3.6 and 3.7 show the power spectra for the divergent wind field with $A=5$ m/s and the rotational wind field with $A=20$ m/s. The difference between the power spectra represented by the thick lines demonstrates the impact of the noise to a clean wind field retrieval. The data smoothing removes some of the noise, the efficiency of the noise removal increases with strength of the data smoothing. We use the terms weak, medium and strong of Table 3.1 for characterizing the strength of the data smoothing.

The smoothness constraint eliminates noise very efficiently, i.e., inhibits the noise of intruding into the retrieved wind components. For the highest frequencies in the spectrum the power of the noise is weakened by about 30 dB. Figure 3.6 and 3.7 further indicate that the two filtering techniques behave similarly: they tend to slant the power spectrum in a way that high frequencies are damped more effectively. Combining the two noise filtering techniques only yields a slight overall improvement.

Reducing the power of the noise can also be accompanied by damping of the wind variation thus inducing bias in the retrieved wind field. The RMSD between the retrieved and analytic wind field in the $u$-component in Table 3.2 and 3.3 give a measure for the accuracy of the horizontal flow. The RMSD are calculated over the entire domain (900 points).

We first note that in the case where no noise was added, the wind is retrieved well (error < 1 cm/s), depending on the truncation condition of the algorithm. The noise
3.4. Experiments in two dimensions

Figure 3.6: The power spectra of the different wind retrieval runs with \( U = 5 \) m/s for the divergent analytic wind field. The power spectra are calculated from the \( u \)-wind component and averaged for all (30) latitudes. SC means smoothness constraint, the other abbreviations are explained in Table 3.1.

Figure 3.7: Same as Figure 3.6, but for the rotational analytic wind field and for \( U = 20 \) m/s.
induces an RMSD of 0.9 m/s in all experiments if no noise filtering is applied. The runs with data smoothing improve the wind field retrieval. For low wind amplitudes ($A=5$ m/s), the RMSD decrease with increasing strength of the data smoothing, for higher analytic wind variation the medium data smoothing (MDS) gives the best results. Using the smoothness constraint generally yields the best accuracy of the wind field retrieval in this analysis. The experiment with the rotational wind field and $A=20$ m/s is an exception: here the medium data smoothing on its own beats the smoothness constraint. A combination of the two noise filtering techniques always produces higher RMSD than the smoothness constraint used on its own. A comparison of the RMSD with the analytic standard deviations in Table 3.2 and 3.3 reveals that the noise-induced deviations can be damped to 4-10% of the analytic standard deviation for the divergent wind field and 9-17% for the rotational wind field. The number of iterations $N$ in Table 3.2 and 3.3 indicate that the wind retrieval’s run-time is significantly better when turning off the smoothness constraint.

Table 3.2: The RMSD in the $u$-component and performance (in number of iterations $N$) for the series of two-dimensional experiments with the divergent analytic wind field. DS means data smoothing, smoothness constraint is abbreviated by SC. The analytic standard deviations for the $u$-component of the three wind fields are 1.33, 2.65 and 5.30 m/s for $A = 5, 10$ and $20$ m/s, respectively.

<table>
<thead>
<tr>
<th>A</th>
<th>5 m/s</th>
<th>10 m/s</th>
<th>20 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RMSD($u$)</td>
<td>$N$</td>
<td>RMSD($u$)</td>
</tr>
<tr>
<td>no noise</td>
<td>0.00</td>
<td>45</td>
<td>0.00</td>
</tr>
<tr>
<td>no filtering</td>
<td>0.90</td>
<td>210</td>
<td>0.90</td>
</tr>
<tr>
<td>weak DS only</td>
<td>0.53</td>
<td>180</td>
<td>0.53</td>
</tr>
<tr>
<td>medium DS only</td>
<td>0.25</td>
<td>128</td>
<td>0.26</td>
</tr>
<tr>
<td>strong DS only</td>
<td>0.18</td>
<td>68</td>
<td>0.29</td>
</tr>
<tr>
<td>SC only</td>
<td>0.12</td>
<td>195</td>
<td>0.15</td>
</tr>
<tr>
<td>SC + medium DS</td>
<td>0.13</td>
<td>224</td>
<td>0.19</td>
</tr>
<tr>
<td>SC + strong DS</td>
<td>0.19</td>
<td>241</td>
<td>0.36</td>
</tr>
</tbody>
</table>

In summary: by using the smoothness constraint we can retrieve an accurate wind field within which the noise is significantly eliminated. A high run-time of the algorithm is required. A quicker retrieval of the two-dimensional wind field can be considered if turning into account a less accurate and noisier product. The data smoothing cannot help to retrieve a wind field which is accurate and smooth at the same time. Section 3.5.1 will discuss the implications of the results found here for thermodynamic applications.
Table 3.3: Same as Table 3.2 but for the rotating analytic wind field. The analytic standard deviations for the $u$-component of the three wind fields are 0.94, 1.87 and 3.75 m/s for $A = 5, 10$ and $20$ m/s, respectively.

<table>
<thead>
<tr>
<th>A</th>
<th>5 m/s</th>
<th>10 m/s</th>
<th>20 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RMSD(u)</td>
<td>N</td>
<td>RMSD(u)</td>
</tr>
<tr>
<td>no noise</td>
<td>0.00</td>
<td>33</td>
<td>0.00</td>
</tr>
<tr>
<td>no filtering</td>
<td>0.90</td>
<td>209</td>
<td>0.90</td>
</tr>
<tr>
<td>weak DS only</td>
<td>0.53</td>
<td>180</td>
<td>0.53</td>
</tr>
<tr>
<td>medium DS only</td>
<td>0.25</td>
<td>127</td>
<td>0.27</td>
</tr>
<tr>
<td>strong DS only</td>
<td>0.21</td>
<td>59</td>
<td>0.35</td>
</tr>
<tr>
<td>SC only</td>
<td>0.16</td>
<td>163</td>
<td>0.23</td>
</tr>
<tr>
<td>SC + medium DS</td>
<td>0.18</td>
<td>196</td>
<td>0.30</td>
</tr>
<tr>
<td>SC + strong DS</td>
<td>0.26</td>
<td>201</td>
<td>0.48</td>
</tr>
</tbody>
</table>

3.5 Experiments including the vertical dimension

3.5.1 Implications for the vertical velocity

Applications for a wind field retrieval often require that further variables are modeled from the horizontal wind components. In the first place amongst these variables is the vertical wind velocity. It is calculated by means of the continuity equation (Section 3.5.3), i.e., by the integration of the divergence being a sum of spatial derivatives of the horizontal wind components. Spatial derivatives are extremely sensitive to noise and their integration can let the errors grow throughout the retrieval domain.

For such a delicate but useful task, we need to investigate the noise filtering techniques further. Retrievals of the three-dimensional wind field including the modeling of the vertical velocity field will be performed in the following experiments. First we outline the principle and model equations as well as the appropriate boundary conditions.

3.5.2 Terminal fall velocity of precipitation

For non-horizontal radar scans the Doppler velocity observed by the radar depends on the vertical velocity component of the scatterer. This vertical component $w$ is the sum of the vertical wind component and the fall speed of the particle $v_z$. Whereas $w$ is a control variable, the terminal fall speed can be parameterized by the reflectivity $\eta$ as in
Chapter 3. Noise Filtering

(3.13).

\[ v_t = a r^b \left( \frac{\rho_0}{\rho} \right)^{0.4} \]  

The constants \( a \) and \( b \) depend on precipitation type, and \( \rho_0 \) is the surface air density. For rain we can assume \( a = -2.6 \) and \( b = 0.107 \) (Joss and Waldvogel 1970). For wind field retrievals where the melting layer is low, information on the fall speed of snow particles is necessary. A parameterization like for rain is difficult because of the large variety of snow particles. It helps, however, that the fall speed for snow particles is smaller (if riming is weak) thus inducing less error. Observations from alternative instruments like vertically pointing radars or optical distrometers should be included to measure or estimate the fall speed of snow particles. Regarding (3.13), we note that the terminal fall speed is so far not filtered, except if a data smoothing is applied to the reflectivity or \( v_t \) directly.

3.5.3 Continuity equation

The continuity constraint is a means for retrieving the vertical velocity \( w \) from the horizontal wind components. The continuity equation is applied in its anelastic form given by (3.14). \((u, v, w)\) is the velocity in the Cartesian coordinates \((x, y, z)\) and \( \rho \) is the air density.

\[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = -\frac{1}{\rho} \frac{\partial \rho}{\partial z} w \]  

(3.14)

In this study the continuity equation is applied as a strong constraint as proposed by Protat and Zawadzki (1999). These authors suggest the weighted combination of a downward and upward integration of the continuity equation. The weight of the upward integration (3.15) linearly decreases with height above ground level \((z - z_b)\), the downward integration dominates the upper level in the inverse manner (3.16).

\[ w_u = 1 - \frac{z - z_b}{z_t - z_b} \]  

(3.15)

\[ w_d = \frac{z - z_b}{z_t - z_b} \]  

(3.16)

\( w_u \) and \( w_d \) are the weights used in the upward and downward integration of the continuity equation, respectively. \( z \) is the absolute level height, \( z_b \) the height of the lowest
3.5. Experiments including the vertical dimension

retrieval level, $z_t$ the top level height. This application avoids the integration of model errors in the vertical direction. The procedure requires known boundary conditions at the bottom and the top of the domain. The boundary condition at the top of the domain assumes that the vertical velocity is zero at the height level half the vertical grid spacing above the highest momentum level, i.e. on an imaginary additional thermodynamic level (Figure 3.1). The vertical grid should extend above the cloud top.

In a similar way the lower boundary condition was assumed in most applications. However, setting the vertical velocity to be zero at the ground is not a realistic proceeding in many mountainous regions in the world. The airflow at lowest altitude must follow the surface of the topography. For this reason we implement the boundary condition proposed by Wüst et al. (1999) and Georgis et al. (2000) considering the topography, by assuming that the flow near the ground is parallel to the topography $h(x, y)$ (3.17).

$$w = \frac{\partial h}{\partial x} + v \frac{\partial h}{\partial y}$$  (3.17)

The numeric implementation is solved as follows: the horizontal wind components $u$ and $v$ from the lowest two momentum levels are interpolated onto the q-points (Figure 3.1). The interpolated values are extrapolated down to the ground surface and the vertical velocity $w_0$ there is calculated by (3.17). $w_0$ is inserted at the lowest thermodynamic level building the strong lower boundary condition. This presumes that the lowest grid levels are close to the ground.

This new boundary condition contributes to the gradient of the cost function by its adjoint (Section 3.2.4). By this the topography constraint can induce additional (but necessary) power to the spectrum of the vertical velocity as well as to the spectrum of the horizontal velocities. We will therefore assume a flat ground ($h=0$ everywhere) for the following experiments.

3.5.4 Results

Three-dimensional experiments are run considering the vertical component of the echo (air motion and fall speed) as explained in Sections 3.5.1 to 3.5.3. The retrieval domain is extended in the vertical to ten levels, for each level the thermodynamic and momentum properties are defined. The lowest momentum level is 0.5 km above ground, such that the grid convention sets the lowest thermodynamic level to the ground. The vertical grid spacing is 1 km. These settings allow the boundary conditions to be fulfilled. Table 3.4 and 3.5 summarize the three-dimensional experiments. We add now the RMS dif-
ferences in the vertical wind component \( w \). All RMSD are calculated over the ten height levels proposed above, i.e., an analysis over 9000 grid points is provided.

Similarly to the two-dimensional experiments in Section 3.4 we note that, in general, applying the smoothness constraint (Section 3.2.3) as a noise filter yields good results only for the accuracy of the horizontal wind component. Again, for large wind amplitudes (20 m/s) the use of a medium data smoothing (definition in Table 3.1) without the smoothness constraint excels the other techniques. The RMSD in the vertical wind component, however, demonstrates the penalty of a data smoothing: in all experiments the RMSD(\( w \)) are larger - by a factor of two or more - than those of using the smoothness constraint only. Note that the RMSD(\( w \)) in Table 3.4 for the experiment without induced noise is higher than for other experiments in the same table. This seeming inconsistency is caused by the fact that discretization noise damages the calculation of the vertical velocity component, because no noise filtering is applied. Comparing the RMSD of the horizontal wind component \( u \) with the analytic standard deviations in Table 3.4 and 3.5 indicates that the noise-induced deviations can be damped to 6-11% of the analytic standard deviation for the divergent wind field and 8-17% for the rotational wind field. For the vertical wind component \( w \) the smoothness constraint lowers the noise-induced RMSD to 14-18% of the analytic standard deviations.

Table 3.4: The RMSD and performance (in number of iterations \( N \)) for the series of three-dimensional experiments with the divergent analytic wind field. The numbers can be compared to the analytic standard deviations for the \( u \)- and \( w \)-components, being 1.55, 3.10 and 6.19 m/s for \( u \) and \( A = 5, 10 \) and 20 m/s, respectively. For the \( w \) the analytic standard deviations are 0.51, 1.01 and 2.03 m/s, respectively.

<table>
<thead>
<tr>
<th>( A )</th>
<th>( 5 ) m/s</th>
<th>( 10 ) m/s</th>
<th>( 20 ) m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSD of</td>
<td>RMSD of</td>
<td>RMSD of</td>
<td></td>
</tr>
<tr>
<td>( u )</td>
<td>( w )</td>
<td>( u )</td>
<td>( w )</td>
</tr>
<tr>
<td>no noise</td>
<td>0.04</td>
<td>0.11</td>
<td>325</td>
</tr>
<tr>
<td>no filtering</td>
<td>0.84</td>
<td>3.00</td>
<td>126</td>
</tr>
<tr>
<td>weak DS only</td>
<td>0.53</td>
<td>1.59</td>
<td>142</td>
</tr>
<tr>
<td>medium DS only</td>
<td>0.26</td>
<td>0.51</td>
<td>169</td>
</tr>
<tr>
<td>strong DS only</td>
<td>0.20</td>
<td>0.18</td>
<td>191</td>
</tr>
<tr>
<td>SC only</td>
<td>0.18</td>
<td>0.09</td>
<td>126</td>
</tr>
<tr>
<td>SC + medium DS</td>
<td>0.17</td>
<td>0.10</td>
<td>133</td>
</tr>
<tr>
<td>SC + strong DS</td>
<td>0.22</td>
<td>0.11</td>
<td>123</td>
</tr>
</tbody>
</table>
3.5. Experiments including the vertical dimension

Table 3.5: Same as Table 3.4 but for the rotating analytic wind field. The numbers can be compared to the analytic standard deviations for the $u$-components, being 1.09, 2.19 and 4.38 m/s for $u$ and $A = 5, 10$ and 20 m/s, respectively. For $w$ the analytic standard deviation is 0 m/s.

<table>
<thead>
<tr>
<th>A</th>
<th>5 m/s</th>
<th>10 m/s</th>
<th>20 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RMSD of</td>
<td>RMSD of</td>
<td>RMSD of</td>
</tr>
<tr>
<td></td>
<td>$u$</td>
<td>$w$</td>
<td>$u$</td>
</tr>
<tr>
<td>no noise</td>
<td>0.00</td>
<td>0.01</td>
<td>339</td>
</tr>
<tr>
<td>no filtering</td>
<td>0.81</td>
<td>2.74</td>
<td>110</td>
</tr>
<tr>
<td>weak DS only</td>
<td>0.51</td>
<td>1.48</td>
<td>115</td>
</tr>
<tr>
<td>medium DS only</td>
<td>0.25</td>
<td>0.45</td>
<td>150</td>
</tr>
<tr>
<td>strong DS only</td>
<td>0.23</td>
<td>0.13</td>
<td>176</td>
</tr>
<tr>
<td>SC only</td>
<td>0.18</td>
<td>0.08</td>
<td>114</td>
</tr>
<tr>
<td>SC + medium DS</td>
<td>0.20</td>
<td>0.07</td>
<td>140</td>
</tr>
<tr>
<td>SC + strong DS</td>
<td>0.30</td>
<td>0.05</td>
<td>139</td>
</tr>
</tbody>
</table>

The power spectra of the three-dimensional experiments show the same basic properties as those of the two-dimensional experiments. Figure 3.8 is an example for the rotational wind field with $A=10$ m/s. We note again, that the application of the smoothness constraint is the most efficient means to filter the noise. Furthermore, the power spectra of the experiments using weak and medium data smoothing and the one using none of the filtering techniques reveal that at the short-wavelength end of the spectrum some noise is eliminated by the adjoint of the continuity equation (Section 3.5.3). This effect loses importance when applying the smoothness constraint.
Chapter 3. Noise Filtering

Figure 3.8: The power spectra of the different wind retrieval runs with \(v=10\) m/s for the divergent analytic wind field. The power spectra are calculated from the \(\nu\)-wind component and averaged for all (30) latitudes. SC means smoothness constraint, the other abbreviations are explained in Table 3.1.

3.6 Conclusions

The experiments in this chapter investigate the effect of two types of noise filtering on the wind field retrieval technique of Protat and Zawadzki (1999), a

- spherical smoothing on the raw radar data and a
- smoothness constraint as a component of the variational analysis technique.

Artificial random noise is added to the analytic wind fields which are to be retrieved from simulated Doppler velocities. In a first series of experiments only the two-dimensional wind field retrieval is examined, i.e., the retrieval of the horizontal wind components. The results indicate that the application of the smoothness constraint eliminates the noise efficiently while producing an accurate wind field. A wind field retrieval featuring merely a data smoothing for noise filtering has the advantage of converging more rapidly towards the minimum of the cost function. However, when strengthening the data smoothing for efficient noise filtering, the wind components become less accurate.

Experiments including the retrieval of the vertical wind by a continuity constraint and appropriate boundary conditions are carried out to analyze the consequences of the
noise filtering techniques for the three-dimensional wind field. They demonstrate the paramount importance of the smoothness constraint for further applications. Applying the smoothness constraint leads to an accurately retrieved and well filtered wind field not only in the horizontal components, but also in the vertical wind component, as well as to a faster convergence rate of the minimization.

The data smoothing, depending on the strength given by the parameters, can efficiently eliminate noise, yet not without damping the wind peaks. This is obvious in the RMSD of all wind components. The data smoothing alters the observations but does not influence the retrieved wind components. The vertical velocity, depending sensitively on the spatial derivatives of these wind components, reflects clearly a lot of the remaining noise in the data. As a consequence, for the use with real radar data, the smoothing has to be applied directly to the reflectivity observations (i.e., indirectly on the terminal fall speed) as well as to the topography data. The application of the smoothness constraint renders these data smoothing runs redundant.

We conclude that if a retrieval of the wind field from radar data is to initialize e.g. a weather forecasting model or any thermodynamic model, where the vertical velocity is of major importance, the smoothness constraint needs to be used. This allows to conserve the typical properties of the wind field and to filter noise in the observations.
4.1 Introduction

The winter storm Lothar having struck on 26 December 1999 was introduced in Section 1.6. The radar images (Figure 1.5) of Lothar impressively reflect the intensive winds of the storm, especially if animated like at http://www.iac.ethz.ch/staff/wueest/lothar/. Tracking the reflectivity pattern by eye one can roughly estimate a mean movement of the echoes of over 30 m/s. The damage of the storm to the forest and to human installations was enormous and hence analyzing the wind fields is imperative. As outlined in Chapter 1, Doppler radars represent favorable instruments to analyze the wind field. However, the high wind speeds of Lothar complicate the Doppler velocity image through multiple folding. These effects need to be corrected. In addition, proper filtering and smoothing techniques are necessary to conserve the characteristic wind structure and its peak values. Chapters 2 and 3 presented a correction technique for aliased Doppler velocities and methods for retrieving reliably the characteristic elements of the three-dimensional wind field. These methods and findings are applied to the Lothar radar data for a wind field analysis. The next sections will summarize the meteorology of the storm event, outline the dealiasing of the PPI scans and provide the corrected observations for a wind field retrieval in Section 4.5.

4.2 Meteorological situation

Figure 4.1 shows the time series of selected meteorological variables at ETH Hönggerberg, Zürich, for 26 December 1999. This weather station is installed next to the radar
Figure 4.1: Meteorological variables measured at the ETH Hönggerberg automatic weather station (545 m a.s.l.) on 26 December 1999. The variables indicate the passage of the occluded front with associated change in wind from more southerly to more westerly direction. The dashed line indicates the maximum wind speed observed in a ten-minute interval. The dotted line indicates 1049 UTC, the time when the center of the NCFR passed ETH Hönggerberg.
location. The passage of the low-pressure system is evident from the pressure trend in the top plot. Several variables indicate the passage of the front: the temperature trend shows a significant increase of 6°C in the morning and a subsequent weaker temperature drop in the afternoon. The warm sector appears compressed: a cold front follows the warm front after approximately 30 minutes. The reason for relatively high temperatures during the two hours after the cold front is unclear. An inversion or stagnant boundary layer air might keep the temperature measurement high. The relative humidity lets distinguish between a humid air mass in the morning and drier air in the afternoon of 26 December. The passage of the warm front is typically accompanied by a change in wind direction from southerly towards westerly origin, and further marked with strengthening wind speeds. However, the maximum wind speed was measured immediately after the cold front passed the station on Hönggerberg. The precipitation observations indicate relatively weak (< 1 mm/h) rain fall during the entire period and maxima during the warm and cold front passage. The cold front around 1045 UTC produced the echo in the radar PPI scans shown in relationship with Lothar in this work, e.g. in Figure 1.5. We will focus on this rainband in the following sections.

4.3 Narrow Cold-Frontal Rainbands

Figure 4.2: Original PPI of reflectivity (left plot) and position and orientation (right plot) of the precipitation cores (PC) in the NCRF of Lothar at 1044 UTC. The single PCs are oriented at an angle of approximately 6° off the alignment of the rainband axis and shifted by approximately 2 km relative to each other.
Houze et al. (1976), Hobbs (1978) and Matejka et al. (1980) identified six classes of mesoscale rainbands in extratropical cyclones. They vary in width and structure and occupy different positions in the cyclone. One of the six types is the narrow cold-frontal rainband (NCFR) straddling the surface cold front and being a few kilometers wide. The most intense rainfall in a cyclone is usually associated with the NCFR. Observations showed that NCFR could not be considered merely as two-dimensional systems, but that they are often organized into a series of relatively intense, ellipsoidal areas of precipitation aligned at an angle to the synoptic cold front axis. These precipitation cores (PCs) are separated by regions of less precipitation (gap regions, GRs) leading to a boudin-like structure on the radar image.

Sketching the contours of the reflectivity maxima of the PPI scan at 1044 UTC on 26 December 1999, as done in Figure 4.2 we note typical characteristics of an NCFR. Precipitation cores are rotated clock-wise by an angle of approximately 6° off the cold front axis. The PCs are separated by gap regions of approximately 2 km width. Albeit the fact that this arrangement appears relatively small in scale if compared to the cases investigated by Hobbs (1978), analog features can be identified. In order to investigate the dynamics of the rainband and to locate the wind maxima, the PPI scans will be dealiased and hence allow to run a wind field retrieval from them.

### 4.4 Dealiasing the PPI scans

The availability of weather radar data for the period where Lothar passed northern Switzerland is as follows: PPI scans of reflectivity and Doppler velocity ($v_z = 16$ m/s) at 1.5° elevation were performed by the ETH Hönggerberg (600 m a.s.l.) radar every five minutes. The MeteoSwiss C-band radar on Albis (928 m a.s.l.), 13.75 km south of the ETH radar provides the operational volume scans consisting of PPI scans at 20 elevation angles (Table 6.2). Aiming at a wind field analysis from the available radar observations the dealiasing of all PPI scans is first required. Because of the lower pulse-repetition-frequency (PRF) and more frequent clutter values, this task is increasingly challenging when processing lower elevations. As an example, the dealiasing of the 1.5° PPI scan from the ETH radar at 1044 UTC is outlined in detail in the following paragraphs.

The raw PPI of Doppler velocity from the ETH radar on Hönggerberg is depicted again in Figure 4.3 to illustrate the effect of the filtering. It shows the existence of several isolated pixels or small isolated pixel clusters which are of little interest for the wind analysis.
4.4. Dealiasing the PPI scans

Figure 4.3: The PPI of Doppler velocity scanned on 26 December 1999 at 1044 UTC by the ETH radar. The antenna elevation was 1.5° from which the dashed isohypses at 1.0 and 2.0 km a.s.l. follow. Some topology of northern Switzerland is drawn with solid lines. Triangles mark the ETH radar (north) and the MeteoSwiss radar on Albis (south).

Figure 4.4: Both figures show the Doppler velocity PPI after the five-neighbor filter and the filter for isolated pixels have acted. Note the differences to the raw state in Figure 4.3. The left figure holds crosses for the positions of the centroids of each region. The right figure shows the marks for artificial shear (x-symbols) and for zero velocity gate pairs (diamond symbols).
Their velocity information is difficult to interpret and verify. The filters mentioned in Section 2.3.1 aim at eliminating these pixels with a five-neighbor filter and consequently by erasing isolated pixels. The filtered PPI (Figure 4.4) shows a 'cleaner' radar image with clearer echo boundaries and less speckle. The relative amount of Doppler velocity pixels lost by the filtering accounts to 7%. In addition to these filters, an artificial data hole of 2 km radius and centered at the radar antenna is created. This is done because in the vicinity of the antenna the variability from gate to gate in the azimuthal direction is large and therefore a high risk for bridging menaces. The size of the hole should depend on the wind speed and the PPI resolution in general.

The segmentation procedure identifies 374 regions, indicated with crosses in Figure 4.4. From personal experience we judge this number to be relatively large, caused by strong folding and inhomogeneous but widespread echoes in the Lothar PPI. The number of regions is a critical number influencing the computing time needed to dealias the PPI. Experiments indicate that without the filtering applied above, the number of regions increases up to the two-fold value. Figure 4.4 further depicts the artificial shear and zero velocity marks identified (Section 2.3.4), however, only every fourth mark is plotted for a better overview. In total, 282 artificial shear marks and 295 zero velocity marks are identified. Visually we can conclude that the marks seize well the positions critical for the continuity of the Doppler velocity pattern.

The environmental wind information is estimated by running a reflectivity tracking (TREC) with the PPI scans at 1039 UTC and 1044 UTC. This yields a horizontal velocity vector \((u_0, v_0) = (32.5, 0.8)\) m/s which is representative for the movement of the rainband in the vicinity of the radar. The environmental wind constraint is applied for gates within 20 km radius from the radar antenna as well as for regions which are not involved in any other constraint ('loose' regions). Figure 4.5 shows where the environmental wind constraints applies.

With the check for the application of the environmental wind constraint the algorithm is prepared for the minimization of the cost function. Figure 4.6 shows the progress of the minimization for the three constraints acting. It indicates that at the beginning the costs of the three constraints are leveled. However, the two constraints for the marks are satisfied after a few iterations, i.e., the continuity is achieved early. The environmental wind constraint dominates the later iterations adjusting the absolute wind speed.

The Nyquist numbers from the minimization, being the control variables of the variational analysis, are real numbers (not integers). This is in contradiction to the definition of the Nyquist number in Section 1.2.1, thus the numbers need to be rounded as recommended in Section 2.4.8. Figure 4.6 gives the histogram of the calculated Nyquist
4.4. Dealing the PPI scans

Figure 4.5: Gray pixels (gates) indicate the application of the environmental wind constraint at their position. White areas contain either missing values or are classified by the algorithm not to be considered by the environmental wind. The coordinates match with those in Figures 4.3 to 4.4.

numbers found. We see clear peaks at Nyquist number -1, 0 and 1, as well as small peak close to Nyquist number 2. From the shading it can be noted that especially the large regions occupy the integer values. This corresponds to what the algorithm is expected to do: the large regions match well with environmental wind and provide a good continuity also near the region boundaries leading to closely fulfilled constraints. Small regions can show inhomogeneities in the wind field or be relics from the clutter filter, thus do not necessarily harmonize with the constraints and cause the smearing of the peaks. As recommended in Section 2.7 the regions with Nyquist numbers between the integers may rather be omitted in the wind field retrieval. For an operational application this is favorable, however, for the analysis here, erroneously dealiased gates/regions can be corrected manually.

Rounding the calculated Nyquist numbers and consequently correcting the Doppler velocity values yields the dealiased Doppler velocity image in Figure 4.7. The image shows the corrected radial velocity pattern. We note a linear structure of decreased Doppler velocity within and co-aligned with the rainband, a structure whose dynamic significance we aim analyzing at. The radial velocity observations are hereby ready for the application of the wind field retrieval. Further ETH PPI scans performed during the intense period of Lothar are successfully dealiased and ready for an analysis.
4.5 Retrieving the wind field

In order to retrieve the wind field, the PPI volume scans are transformed on a three-dimensional Cartesian grid, i.e. transformed to a CAPPI (constant-altitude-PPI). The transformation is performed using the technique proposed by Wüst (1998). This method considers both horizontal and vertical gradients to determine the value at each grid point and avoids ring artifacts and other undesired effects as if using a nearest-
4.5. Retrieving the wind field

Figure 4.7: The dealiased PPI of the ETH radar, scanned at 1044 UTC during Lothar and at 1.5° elevation, is depicted. The general westerly flow is now visible as well as a linear structure within the rainband which will be discussed in Section 4.5. The positions of the ETH H"onggerberg (north) and the MeteoSwiss Albis (south) radar are indicated with triangle symbols.

neighbor method. Since the Albis radar composes a full volume scan of two separately scanned, staggered half-volume scans, and since the movement of the NCFR is fast, only one half-volume scan is considered in the following. These ten elevations were scanned within two minutes starting at 1045 UTC. From the ETH radar, only the 1.5° elevation is available but nevertheless transformed on the same three-dimensional grid as used for the Albis radar data. The grid spacing is 500 m in the horizontal and vertical. Twelve height levels from 0.5 to 6.0 km a.s.l. are used, where the upper limit is above the echo top.

Since the dealiased observations from two Doppler weather radars, the ETH H"onggerberg and the Albis radar (MeteoSwiss), are available for the lowest elevation, a dual-Doppler wind field retrieval is applicable at low altitude. The wind field retrieval method applied here was outlined in Section 3.2. The radial velocity vectors from both radars can be combined to yield two components of the three-dimensional wind vector. The third component can be retrieved with physical constraints (continuity equation). A dual-Doppler method is only to be applied in the so-called dual-Doppler region, within which each point projects an appropriate viewing angle (usually greater than 30° and lighter than 150°) towards both radars. The dual-Doppler region consists of two circles intersecting each other at the two radar positions (Figure 4.8). The intersection area is
factored out. Outside the dual-Doppler region and at higher altitude, where the 1.5
scan of the ETH radar is not representative, the single-Doppler constraints (Section
5.2) apply and help to derive the wind field.

The observations from the ETH radar need to be corrected for the fast movement of
the NCFR, since they are not taken at the same time as the half-volume scan of the
Albis radar. 10:45:30 UTC, the time at which the 1.5° PPI was scanned with the Albis
radar, is taken as the reference time for the following analysis. The two PPI scans from
the ETH radar at 1044 UTC and 1049 UTC are combined to a virtual PPI at 10:45:30
UTC using the following scheme: From the ETH radar scans at 10:44 UTC (t_−1) and
10:49 UTC (t_+1) a reflectivity tracking algorithm (TREC, see Section 1.5) using lagged
correlations is performed, in order to estimate the mean movement of the rain band.
This yields a horizontal velocity vector \( \vec{v}_0 = (32.5 \text{ m/s}, 0 \text{ m/s}) \). This movement of the
NCFR is considered in a linear interpolation of the two ETH reflectivity PPI scans onto
the time 10:45:30 UTC (t_0) by using (4.1). \( z \left[ \vec{x}, t \right] \) is the reflectivity at the position \( \vec{x} \) and
time \( t \).

\[
\begin{align*}
z \left[ \vec{x}, t_0 \right] &= \frac{t_+ - t_0}{t_+ - t_--1} z \left[ \left( \vec{x} + (t_--1 - t_0) \vec{v}_0 \right), t_-1 \right] \\
&\quad + \frac{t_0 - t_--1}{t_+ - t_--1} z \left[ \left( \vec{x} + (t_+1 - t_0) \vec{v}_0 \right), t_+1 \right]
\end{align*}
\]

(4.1)

For the radial velocity \( v_r \) the same issue becomes more sophisticated because the
measurement is geometrically oriented. I.e., if an observation is virtually shifted relative
to the radar antenna, the observation needs to be adapted as in (4.3).

\[
\begin{align*}
v_r &= \frac{ux + vy}{\sqrt{x^2 + y^2}} \\
dv_r &= \frac{\partial v_r}{\partial x} dx + \frac{\partial v_r}{\partial y} dy
\end{align*}
\]

(4.2) (4.3)

dv_r describes the change in radial velocity when shifting an observation virtually by an
infinitesimal vector \((dx, dy)\). If assuming linear motion and development, this vector can
be set to the result of the reflectivity tracking multiplied with the time interval between
the regarded PPI scans. Because the horizontal wind vector \((u, v)\) is unknown, it must
be assumed equal to the tracking vector as well. The correction \( dv_r \) is strongest in the
vicinity of the radar and 90° off the wind direction. However, gates which as to speak
pass the antenna, i.e., change their azimuth by more than 30° are erased, because
the linear assumption is critical. The procedure for the dealiased Doppler velocity is thus to 1) correct the observations for the altered geometry first, and afterwards to 2) interpolate it as proposed for the reflectivity in (4.1).

Figure 4.8: The top left CAPPI at 1.5 km a.s.l. shows the dealiased Doppler velocity from the ETH radar with the dual-Doppler regions’ circles (see text) added. Triangles mark the positions of the two radars. The top right CAPPI shows the same sector and height level, but the dealiased Doppler velocity of the Albis radar (MeteoSwiss) is visualized. The bottom plot depicts the retrieved horizontal wind vectors with the reflectivity underlaid.

Though the scan time of the 1.5° PPI from the Albis radar serves as the reference
time, a correction needs to be performed for the remaining PPIs of the half-volume scan. However, the two preceding volume scans were not stored correctly by the radar computer causing the data to be missing. Using even earlier scans for the correction is expected to induce larger errors than the asynchronity itself. The correction (4.1) was hence simplified to consider merely the shift of the rainband without interpolating two time steps. Since the maximum offset to the reference time is smaller than two minutes, the errors can be considered to be of minor importance.

With (4.1) to (4.3) the linear temporal development of the PPI scans can be considered, such that the images of the two radars can be assumed simultaneous. The wind field retrieval algorithm is run using the same grid parameters as given by the PPI/CAPPI images. The domain is placed to cover the majority of the dual-Doppler region including the rainband. Outside the dual-Doppler region the wind arrows are initialized with the reflectivity tracking vector (32.5,0.0) m/s, what is required for quality single-Doppler retrievals (Chapter 5). Noise filtering is performed as recommended in Chapter 3, i.e., the smoothness constraint is applied while the data smoothing is omitted. Assuming correct dealiasing of the Doppler velocity observations, what is visually verified, and estimating the instrumental error in the Doppler velocity measurement to account to approximately 1 m/s, the expected geometrical error in the horizontal wind components can be limited to 2 m/s (Figure 5.1). Sensitivity studies were carried out to estimate the error induced by retrieving the wind from elevated PPI scans. The vertical wind profile estimated from a VVP was considered to correct the velocities for this purpose. The results indicated no significant change of the wind pattern.

4.6 Interpretation

Figure 4.8 shows the dealiased Doppler velocities of both radars for the wind retrieval domain as well as the retrieved horizontal wind vectors at 1.5 km a.s.l. The vectors reflect the general westerly flow also estimated from the reflectivity tracking, but in addition reveal details about the flow. Ahead of the front (in the south-east) the wind direction possesses an evident southerly wind component causing horizontal wind shear along the rainband. The wind speed (magnitude of the retrieved wind vectors) is visualized in the left diagram in Figure 4.9. In contradiction to the dynamics of NCFRs found by Hobbs and Persson (1982) and Wakimoto and Bosart (2000), the maximum wind speeds are at the trailing edge of the NCFR and behind the core region. Maximum wind speeds are usually expected ahead of the NCFR causing strong horizontal wind shear within the cores. The pattern of the horizontal divergence \(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\) and
the storm-relative winds in the right diagram in Figure 4.9 show that the core regions coincide with regions of maximum convergence. The convergence causes updrafts and with this growth of precipitation particles.

The expected horizontal wind shear is best expressed in terms of vertical vorticity $\zeta = \partial v/\partial x - \partial u/\partial y$. The horizontal distribution of $\zeta$ in Figure 4.10 indicates strong negative vertical vorticity induced at the center of the precipitation core through the increasing westerly wind behind the core. The magnitude of this shear exceeds the one of the positive vorticity ahead. The negative vertical vorticity being the dominant shear feature in the NCFR was not observed in other NCFRs. The relative vorticity values are yet consistent with the pattern found by Hobbs and Persson (1982). It suggests a wave-like structure following the cores’ positions. Whereas Wakimoto and Bosart (2000) found vorticity isolines crossing the core regions, they lead 'around' the cores such that the wind shear is placed along the entire length of the cores of the Lothar NCFR. Because of the limited dual-Doppler region only a fragment of the wave-like structure is visible.

A common practice to determine the position of the cold front from dual-Doppler measurements is to use the location where the component of relative flow perpendicular to the front is zero (Carbone 1982, Locatelli et al. 1995). Wakimoto and Bosart (2000) proposed to use the gradient of vertical vorticity for determining the kinematic position of the front, since this variable is not dependent on the determination of the frontal motion and orientation. The vorticity gradient is well visible in Figure 4.10 and appears to be maximum just ahead of the maximum reflectivity values. The right diagram in Figure 4.10 shows a vertical vorticity profile through the precipitation core and normal to the frontal line at 10:45:30 UTC. The negative vorticity anomaly is dominant at lower altitudes beneath 2.5 km a.s.l. Above this height the positive anomaly, which is relatively weak at low altitude, becomes dominant. The characteristic horizontal gradient of vertical vorticity is slanted towards the back of the NCFR. This axis represents the typical cold-frontal vertical profile, i.e., cold air mass propagates and lifts the warmer air.

The wind fields retrieved in this Chapter were provided for an analysis of the correlation between winds and damage patterns during Lothar by Schmid et al. (2001). The wind fields are derived at a spatial resolution excelling the one of ground measurements and at high temporal resolution, thus providing a favorable means to investigate the origin of the damage. A drawback is that the ground winds which are responsible for the destruction cannot be measured, since the antenna elevation, shielding etc. often hinder observations close to the earth surface. Despite this fact we assume the ground winds to be related to the wind pattern a few 100 m aloft.

The pattern of the damage to the forests in northern Switzerland is depicted in Schmid
Figure 4.9: Left plot: The same sector and ground-relative wind vectors as in Figure 4.9 are shown, but with the horizontal wind speed contoured underneath. Solid line contour the reflectivity. Right plot: The divergence in units of $10^{-1}$ s$^{-1}$ is colored and storm-relative winds $(u-[32.5 \text{ m/s}],v)$ are drawn. The reflectivity is contoured with solid lines to indicate the position of the core region.

et al. (2001) and WSL and BUWAL (2001) (page 67) and shows parallel bands oriented from West to East, separated by a few tens of kilometers. These bands are suggested to coincide with the tracks of the core regions in the NCFR. The maximum wind speeds observed behind the core regions (Figure 4.8) damaged the forests when the NCFR passed. This suggestion is subject to an ongoing project (see Section 7.4).
Figure 4.10: Left diagram: Close-up on the left half of the dual-Doppler region where one core region is located. The vertical vorticity $\zeta$ in units of 1000/s is indicated with filled contours. Negative vorticity is present 'behind' the core region, positive ahead. Solid lines mark the isogons of the wind direction. Right diagram: The cross-section of vertical vorticity $\zeta$ through the NCFR along the line from A to B indicated in the left plot (657/250 to 675/228 km) is shown. The slanted cold front can be located by the large horizontal vorticity gradient.
Chapter 5

**SinglePlus-Doppler wind field retrieval**

5.1 Introduction

In Chapter 1 several methods to retrieve the wind field from Doppler weather radar observations were summarized. One aspect to classify them is to separate multiple-radar from single-radar techniques. Multiple-Doppler radar techniques require dense radar networks for their advantages to be developed. Geometrical relationships, roughly the viewing angle to the radar antennae, define the error structure in the range of the radars (Ray et al. 1979, Doviak et al. 1976). Because Doppler velocity observations represent the radial velocity of the scatterers, the errors in the horizontal wind field are best expressed with the help of the expected errors in the cross-beam wind component $v_{cb}$.

$$v_{cb} = \frac{ux - uy}{|x, y|}$$  \hspace{1cm} (5.1)

$(u, v)$ are the Cartesian wind components at the position $(x, y)$, geometrically calculated from $v_{r1}$ and $v_{r2}$, the radial velocities observed with the two radars, respectively. I.e., $(u, v)$ are functions of $v_{r1}$ and $v_{r2}$. The expected error in $v_{cb}$ is expressed as in (5.2).

$$\Delta v_{cb} = \Delta v_{r1} |\partial v_{cb}/\partial v_{r1}| + \Delta v_{r2} |\partial v_{cb}/\partial v_{r2}|$$  \hspace{1cm} (5.2)

Assuming horizontal radar scans $\Delta v_{cb}$ is only dependent on the errors $\Delta v_{r1}$ in the measurement of the radial velocity and the position relative to the radar antennae. The former’s uncertainties are congruent to those of the Doppler velocity, i.e., the variety of scatterers and their motion as well as aliasing of the Doppler shift dominate the errors.
Chapter 5. SinglePlus-Doppler wind field retrieval

After the aliasing is corrected $\Delta v_{r1}$ is estimated to account to approximately 1 to 2 m/s. Figure 5.1 visualizes $\Delta v_{cb}$ normalized to $\Delta v_{r1} = 1$ m/s for the dual-Doppler configuration including the ETH Hönggerberg radar and the MeteoSwiss radar on Albis.

Figure 5.1: The horizontal distribution of the error in the cross-beam wind component when retrieving the wind from a dual-Doppler configuration. The errors are given in m/s for an uncertainty in the radial velocity observations of 1 m/s. The radar antennae are marked with triangle symbols.

Figure 5.1 indicates increasing errors when approaching the elongated baseline of the radars and when increasing the range. The least errors can be reached in two circular areas intersecting each other at the radar positions. This geometrical relationship corresponds to the requirement of an appropriate viewing angle to both radars. For practical use, a minimal viewing angle of 30° or 45° is usually determined. This limits dual-Doppler applications to regions as depicted in Figure 5.2. This requirement was used for the studies in Chapters 3 and 4 and is satisfied in the following experiments.

In general, the density of Doppler radar networks is too poor to provide multiple-Doppler wind fields for the entire radar range coverage. In the areas outside a multiple-Doppler region a single-Doppler method can be applied to retrieve the horizontal wind field. In this study it is investigated to what extent single-Doppler wind field retrievals can be improved by including supplementary wind information of different types. Supplementary wind information, on the one hand, can be weather radar-derived like a VAD/VVP, tracking products or Doppler velocity observations, or on the other hand origin from wind-profilers (vertically pointing L-band radars) or numerical models. The different wind information categories will be simulated for a series of case studies. The following section describes the single-Doppler wind field retrieval method. An error analysis
5.2. The single-Doppler technique

Figure 5.2: The dual-Doppler regions (gray) for two Doppler radars if a viewing angle of 45° (left plot) and 30° (right plot) is required. Geometrically reliable dual-Doppler wind vectors can only be retrieved within the gray regions.

judges the impact of the supplementary wind information.

5.2 The single-Doppler technique

The multiple-Doppler wind field retrieval algorithm by Protat and Zawadzki (1999) was outlined in Chapter 3 as an extension of the single-Doppler technique by Laroche and Zawadzki (1994). The general idea underlying the multiple- and the single-Doppler version is identical, however, constraints for the observations (radial velocities in the first place) of additional radars or bistatic receivers (Wurman et al. 1993) were added. In the same move two features of the single-Doppler technique could be omitted. These will be roughly illustrated here to help to understand the method of Laroche and Zawadzki (1994).

A major difference between a pure multiple-Doppler radar technique and a technique using one Doppler radar is that the single-Doppler wind retrieval is dependent on the initialization of the control variables (Section 3.2.1), i.e. the wind vectors. Because two constraints (Section 3.2.1) for radial velocities are acting on the control variables in the case of a multiple-Doppler radar retrieval, there is no degree of freedom in the horizontal direction and the initialization only serves the acceleration of the minimization procedure. One radial velocity constraint on its own can only linearly stretch the model wind vectors yet not rotate them. This is given by the fact that the gradients of the cost function with respect to \( u \) and \( v \) are identical. Other constraints like the smoothness constraint can rotate the vectors. The consequences will be discussed in the following.

Because the observations of the Doppler velocity do not directly yield information about the tangential component of the movement of the echo, an additional constraint guiding
the wind retrieval algorithm was designed for the single-Doppler wind field retrieval by Qiu and Xu (1992) and Laroche and Zawadzki (1994). It considers the conservation of reflectivity along the movement vector of the echo as in (5.3). In other words, the echo is to be transported to the correct spot regarding the PPI scans before and after the time of interest. Hence, at least two subsequent PPI scans must be available.

\[
\frac{\partial \eta}{\partial t} + \frac{\partial (u \eta)}{\partial x} + \frac{\partial (v \eta)}{\partial y} + \frac{\partial ((w + v_t) \eta)}{\partial z} = S_\eta
\]

(5.3)

\(\eta\) is the reflectivity, \((u, v, w)\) is the three-dimensional wind vector and \(v_t\) the fall speed of the precipitation as explained in Section 3.5.2. \(S_\eta\) is a source-sink term for reflectivity, which will be set to zero for simplification in the following.

The wind field retrieval algorithm used in this study features the initialization of the model wind fields with VVP information and constrains the wind model with the conservation of reflectivity (5.3). This algorithm allows both retrieving single-Doppler as well as multiple-Doppler wind vectors, using whatever wind information is available.

## 5.3 Methods

Six case studies, where both the ETH Hönggerberg and the MeteoSwiss Albis radar were operated, are selected for analyses. The list is compiled in Table 5.1. They include both stratiform precipitation and convective summer storms. In the generally stratiform system of 28 August 1997, embedded convective cells were observed and investigated separately in case study I. Figure 5.3 shows the geographic overview for the retrieval domains of each case study in Table 5.1, all being located within the dual-Doppler region of the two radars involved.

The observations of the MeteoSwiss radar on Albis are handled to simulate supplementary wind information. Their horizontal resolution is artificially reduced using two methods:

- **Averaging**: The Doppler velocity data are averaged over a given number \(s\) of grid points. This can be interpreted as a simulation of data from a distant radar, a numerical model etc. (Figure 5.4A).

- **Undersampling**: On a regular basis, Doppler velocity observations are erased (set to missing values) in the image. There remain punctual observations every \(s\)-th grid point representative for only a small area (the pulse volume) in the retrieval
5.3. Methods

Table 5.1: The case studies investigated for varying supplementary wind information. The last column indicates the dominating character of the events (domains) which may vary locally. The wind retrieval domains for each case study are plotted in Figure 5.3.

<table>
<thead>
<tr>
<th>Case study</th>
<th>Date</th>
<th>Time (UTC)</th>
<th>Dominating character</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>28 Aug 1997</td>
<td>1311</td>
<td>embedded convective cell</td>
</tr>
<tr>
<td>II</td>
<td>28 Aug 1997</td>
<td>1311</td>
<td>stratiform rainfall</td>
</tr>
<tr>
<td>III</td>
<td>11 Jan 1999</td>
<td>1430</td>
<td>stratiform snowfall</td>
</tr>
<tr>
<td>IV</td>
<td>11 Jan 1999</td>
<td>1430</td>
<td>stratiform snowfall</td>
</tr>
<tr>
<td>V</td>
<td>05 Jun 2000</td>
<td>1524</td>
<td>convective storm</td>
</tr>
<tr>
<td>VI</td>
<td>13 Jun 2000</td>
<td>1819</td>
<td>convective storm</td>
</tr>
</tbody>
</table>

Figure 5.3: Overview on the wind retrieval domains (square boxes) used in the case studies I to VI. The boxes are labeled with codes described in Table 5.1. The triangles mark the positions of the two radars (ETH Hönggerberg north, MeteoSwiss Albis south). The circles mark the dual-Doppler regions.

Anemometers, wind profilers and other in-situ wind measuring devices provide this type of information (Figure 5.4B), though not on a regular grid as simulated here.
Figure 5.4: Schematic representation of the two methods to reduce the spatial resolution the Doppler velocities from the second radar. Scheme A) Averaging over \( s \) grid points. Scheme B) Undersampling by keeping every \( s \)-th sample. An example is given in Figure 5.5.

The resolution reduction factor \( s \) is chosen 2, 4, 10 or 20 for both averaging and undersampling. \( s = 0 \) indicates the original Doppler velocity field, i.e., a dual-Doppler retrieval using these data represents the most reliable wind field retrieval, and serves as the reference field for the error analysis (5.4). Section 5.1 calculated the expectable errors for this case.

For each case study the following wind field retrieval runs are carried out:

- A single-Doppler retrieval with 1) initialization of the horizontal wind field using the VVP from the ETH radar and a single-Doppler retrieval with 2) initialization with zero velocity wind vectors.

- Dual-Doppler wind retrievals after having averaged the Doppler velocity image of the Albis radar using averaging with \( s=[2,4,10,20] \). The initialization of the wind field is redundant in this case.

- Dual-Doppler wind retrievals after having reduced the Doppler velocity image of the Albis radar using undersampling with \( s=[2,4,10,20] \) with 1) initializing the wind field with zero velocity values and after 2) initializing the wind field using VVP data.

Because the horizontal resolution of the Cartesian Doppler velocity data is 500 m for all case studies, the values of \( s=[2,4,10,20] \) yield a resolution of \([1,2,5,10]\) km, respectively. The retrieval domains are 10x10 km wide and have an additional margin of 5 km, necessary for a properly functioning reflectivity conservation constraint. Additionally to the mentioned constraints, the smoothness constraint is applied as recommended in Chapter 3.
5.4. Results

The quality of the retrieved wind field is estimated using the mean difference \( \epsilon_{cb} \) (5.4) in the cross-beam wind component \( v_{cb} \) (relative to the ETH radar) between the wind retrieval from the reduced observations and the dual-Doppler reference retrieval \( v^0_{cb} \).

\[
\epsilon_{cb} = \sum_{i=1}^{N} (v_{cb}(i) - v^0_{cb}(i))
\]  

(5.4)

\( N \) is the number of grid points in the domain (400 for all case studies), \( i \) an index value for a grid point. The cross-beam wind component \( v_{cb} \) is geometrically calculated using (5.1). The standard deviation \( \sigma_{cb} \) of the differences in the cross-beam wind components is calculated to provide the second moment of the errors.

\[
\sigma_{cb}^2 = \frac{1}{N-1} \sum_{i=1}^{N} \left[ (v_{cb}(i) - v^0_{cb}(i)) - \epsilon_{cb} \right]^2
\]  

(5.5)

5.4 Results

Figure 5.5 demonstrates the effects of averaging and undersampling with \( s = 4 \) for case study III. Larger \( s \) decreases the available observations even further, such that for \( s = 20 \) only one sample remains centered in the domain. In order to illustrate the behavior of a single-Doppler and a dual-Doppler wind retrieval run, Figures 5.6 and 5.7 compare the two techniques for both a weakly convective situation (case study I) and a convective storm (case study VI). As mentioned above, the dual-Doppler wind fields on the left-hand side in the figures serve as the reference field for the error analysis. In Figure 5.6 the convergence line is roughly reproduced with the single-Doppler technique, but the northern wind component north of the line is too strong. The convective summer storm in Figure 5.7 shows a more complex wind field. Though the characteristic pattern can be recognized in the single-Doppler winds, the vectors differ from the dual-Doppler arrows, especially in magnitude.

The error analysis is visualized in Figure 5.8. For each case study the mean error in the cross-beam wind component is plotted as a thick line and the mean cross-beam error plus/minus the standard deviation with thin lines. Different line styles let distinguish between averaging and undersampling, as well as different initialization methods. As expected, the errors decrease with increasing resolution of the supplementary wind information. The single-Doppler wind field retrievals indicate a strong dependence on the initialization. If the initialization is omitted, the largest errors are found. The curves
Figure 5.5: The two ways to artificially reduce the resolution of the Doppler velocities from the second (Albis) radar shown at the example of case study III (Table 5.1) and resolution reduction factor $s = 4$. The top plot shows the original Doppler velocity observation. The bottom left plot holds the averaged values produced by averaging. The bottom right plot shows what is left after undersampling the observations.

for undersampling reveal that increasing the resolution of supplementary wind information does not improve the retrieval of the wind in a linear manner. As single, punctual measurements dominate the wind information, their local variation is induced into the retrieved wind field. The smallest errors in general are achieved by using averaged supplementary wind field information. In the stratiform situations, where the wind field is more homogeneous, the wind field is expected to be relatively homogeneous and
5.5. Conclusions

Figure 5.6: Sample comparison of the wind field retrieved for case study I with the dual-Doppler technique without reducing the second radar’s observations (left plot) and the single-Doppler method initialized with a VVP (right plot). The convergence is reproduced with the single-Doppler, however, the northern part of the domain shows an erroneous northerly wind component. The location of the domain is shown in Figure 5.3.

in good agreement with the mean wind. However, in convective situations, averaging might be accompanied by losing detailed information. The domain size and grid spacing allow to resolve the vorticity structure as can be seen from Figure 5.7. Nevertheless, case studies V and VI as well as the less convective experiment I yield best results when averaging. The standard deviations of the differences in the cross-beam wind component reveal that though the mean wind is well retrieved, small-scale structures have vanished.

5.5 Conclusions

The case studies show the need of the initialization in a single-Doppler wind field retrieval using a reliable background wind estimate. If the wind field in the objective analysis is properly initialized, the mean error in the cross-beam wind component in the case studies does not exceed 2 m/s in the stratiform situation and 3.5 m/s during convective storms. The standard deviations of the errors seem to increase with the degree of convection. Comparing the errors to the mean wind speeds indicated in Figure 5.8, we
note that the errors are of the order of the wind speeds in case study VI. To retrieve the complex wind pattern in this storm cell (Figure 5.7), supplementary wind information is necessary. If wind observations from a remote sensing instrument or punctual wind measurements are available, they can be included in the wind field retrieval algorithm and improve the quality of the retrieval. The results indicate a higher reliability of averaged but larger-scale wind information for this purpose, than punctual wind observations.

Punctual supplementary wind information, in the first place, fixes a single grid point in the wind retrieval domain. The smoothness constraint ‘transports’ this information from the punctual wind measurements to neighbored grid points. Hence, the smoothness constraint influences the wind field retrieval using undersampling in a somewhat stronger way, as the radial velocity constraint only acts at a few number of grid points. If punctual observations are included in a wind retrieval initialized with zero velocity, the smoothness constraint is responsible for ‘establishing’ a cross-beam wind component between the points of observation. This is identical to the statement in Section 5.1 that the smoothness constraint can rotate wind vectors (because $\partial J/\partial u$ is not equal to $\partial J/\partial v$). This rotation is yet an adjustment on a relatively small scale (Chapter 3). Because of multiminima and for performance reasons (number of iterations of the minimization), the initialization using a reliable background wind field is necessary.

This chapter quantified the errors which need to be expected when retrieving the wind field from multiple Doppler radars or a single Doppler radar supported by supplementary wind information. This error analysis is to be regarded in the appropriate context: Radar
Figure 5.8: The mean (thick lines) cross-beam errors (5.4) for the six case studies. Each diagram shows the error versus the artificial resolution of the Albis radar. SD abbreviates 'single-Doppler' which exceeds the scale of the x-axis. Thin lines indicate the mean error plus/minus the standard deviation of the error (5.5). The mean wind speed (mws) in the domain for each case study is indicated in the lower left corner of the diagrams.
observations excel through their high resolution in space and time. Since only few alternative wind observations are available to be compared, the error analysis herein uses dual-Doppler winds as a reference. If a wind vector is to be retrieved for a particular spot at a given time, its error will be influenced by additional sources, some of which concern the problems of remote sensing instruments in general. The representativity of a Doppler velocity observation is confined to the pulse volume, given by the beam width, the pulse length and the elevation angle. This pulse volume grows with the distance from the radar and reaches higher altitude in the atmosphere at the same time. One cubic-kilometer might be a good estimate for the volume of a typical radar pulse volume at midrange. When comparing a Doppler velocity value, being roughly the first moment of the velocity distribution of the scatterers in this volume, to other wind observations or using it for any application, those effects and uncertainties need to be considered also, in addition to the error analysis of this chapter.
Chapter 6

Operational Wind Field Retrieval in Switzerland

6.1 The Swiss Radar Network

MeteoSwiss (formerly known as the Swiss Meteorological Institute SMI) has installed three operational C-band Doppler weather radars in Switzerland. An overview about the instruments, the network and the products created from them is given by Joss et al. (1998). This section briefly outlines the aspects of the radar network important for an operational wind field retrieval.

The three radar instruments of the Swiss radar network are basically identical. Some technical specifications of the radar instruments are given in Table 6.1. Several parameters are important for retrieving the wind field: the beam width and the pulse length pre-determine the maximum spatial resolution of the product, the pulse repetition frequency and the transmitter frequency (or the signal wavelength) determine the Nyquist velocity and with this the frequency of aliasing of the Doppler velocities. The parameters as well as the scan strategy are permanently set for operational purposes. The scan strategy features two half-volume scans repeated every five minutes. They consist of PPI scans interleaved in the elevation angle as shown in Table 6.2. The PPI scans of reflectivity and Doppler velocity are provided with a maximum range of 130 km (for the lowest elevations), with 1° azimuthal and 1 km radial resolution. Table 6.2 indicates the change of the pulse repetition frequency (PRF) with elevation angle. As an important consequence, the lowest four PPI scans feature a Nyquist velocity of 8.25 m/s leading to frequent aliasing of the Doppler velocities. The lower pulse repetition frequency, which causes the low Nyquist velocity, in return allows for a higher range $r_a$. 
Table 6.1: Some specifications of the Swiss radar instruments. Taken from Joss et al. (1998).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna half-power beam width</td>
<td>1.0° nominal (Q3 dB)</td>
</tr>
<tr>
<td>Transmitted power</td>
<td>250 kW nominal</td>
</tr>
<tr>
<td>Pulse length</td>
<td>0.5 μs nominal</td>
</tr>
<tr>
<td>Transmitter frequency</td>
<td>5430 to 5450 MHz depending on antenna</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>2 MHz nominal</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>25,000 (44 dB) nominal</td>
</tr>
<tr>
<td>Losses</td>
<td>5.7 dB (Dole), 7.6 dB (Lema), 12.3 dB (Albis)</td>
</tr>
<tr>
<td>Noise Figure</td>
<td>1.52 (1.8 dB) nominal</td>
</tr>
<tr>
<td>Receiver noise k<em>T</em>B</td>
<td>-110.4 dBm</td>
</tr>
<tr>
<td>Sensitivity for rain at 230 km</td>
<td>0.16 mm/h nominal</td>
</tr>
<tr>
<td>Number of elevations</td>
<td>20 in 5 min</td>
</tr>
<tr>
<td>Antenna revolutions/min</td>
<td>3, 4 or 6 (depending on antenna elevations)</td>
</tr>
<tr>
<td>PRF (pulse repetition frequency)</td>
<td>600, 800 or 1200 Hz (dep. on el.)</td>
</tr>
<tr>
<td>Wavelength</td>
<td>5.5 cm</td>
</tr>
<tr>
<td>Transmitter type</td>
<td>Magnetron</td>
</tr>
<tr>
<td>Side lobes (excluding radome)</td>
<td>max -30 dB</td>
</tr>
<tr>
<td>Dry radome attenuation</td>
<td>less than 0.35 dB one way nominal</td>
</tr>
<tr>
<td>Receiver: log amplifier</td>
<td>90 0.5 dB nominal</td>
</tr>
<tr>
<td>Samples per degree and per km</td>
<td>32 x 12</td>
</tr>
<tr>
<td>Processed Video signals</td>
<td>I, Q, log-Z, resolution: 12 bits</td>
</tr>
<tr>
<td>Clutter suppression</td>
<td>6 complementary tests, including dynamic map</td>
</tr>
<tr>
<td>Calibration with noise source</td>
<td>every 2.5 min</td>
</tr>
<tr>
<td>Calibration with signal generator</td>
<td>fully automatic, 121 points every 24 hours</td>
</tr>
<tr>
<td>Profile corrections</td>
<td>visibility, profile estimated in real time</td>
</tr>
</tbody>
</table>

The Swiss weather radar network, together with the United Kingdom’s network belongs to the densest radar networks worldwide. The weather radars (triangle symbols in Figure 6.1) on La Dôle (in the Jura) and Albis (near Zürich) cover the majority of the Swiss Plateau and northern Alps, as well as marginal parts of France and Germany. The Monte Lema radar observes precipitation systems on the south side of the Alps, i.e. the Ticino plus adjacent parts of Italy. The Alps split Switzerland into a northern and a southern part, being an unfavorable aspect for radar meteorology. The complex structure of mountains and valleys shield a large but incoherent area of the country from
6.1. The Swiss Radar Network

Table 6.2: The scan strategy of the MeteoSwiss radars. A volume scan is observed in an interleaved mode: the first ten elevations are scanned in the first 130 seconds, then the next ten elevations are performed. The table lists the elevations of the scans, the elevation change ($\Delta$Elev.), the ranges for reflectivity and Doppler velocity scans ($r_{a,z}$ and $r_{a,v}$), the antenna revolutions per minute (RPM), the duration of a scan (time), the time needed to change the elevation (step), the pulse repetition frequency (PRF) and the Nyquist velocity ($v_a$).

<table>
<thead>
<tr>
<th>n</th>
<th>Elev.</th>
<th>$\Delta$Elev.</th>
<th>$r_{a,z}$ [km]</th>
<th>$r_{a,v}$ [km]</th>
<th>RPM [1/min]</th>
<th>Time [s]</th>
<th>Step [s]</th>
<th>PRF [1/s]</th>
<th>$v_a$ [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.3</td>
<td>1.8</td>
<td>230</td>
<td>130</td>
<td>3</td>
<td>20</td>
<td>1.4</td>
<td>600</td>
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<td>2</td>
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<td>3</td>
<td>20</td>
<td>1.4</td>
<td>600</td>
<td>8.25</td>
</tr>
<tr>
<td>3</td>
<td>3.5</td>
<td>2.0</td>
<td>162</td>
<td>130</td>
<td>4</td>
<td>15</td>
<td>1.4</td>
<td>800</td>
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<td>2.0</td>
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<td>4</td>
<td>15</td>
<td>1.4</td>
<td>800</td>
<td>11.00</td>
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<tr>
<td>5</td>
<td>7.5</td>
<td>2.0</td>
<td>85</td>
<td>85</td>
<td>6</td>
<td>10</td>
<td>1.4</td>
<td>1200</td>
<td>16.50</td>
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<td>6</td>
<td>9.5</td>
<td>3.5</td>
<td>68</td>
<td>68</td>
<td>6</td>
<td>10</td>
<td>1.7</td>
<td>1200</td>
<td>16.50</td>
</tr>
<tr>
<td>7</td>
<td>13.0</td>
<td>5.3</td>
<td>51</td>
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<td>16.50</td>
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Though the radars cannot see into all Alpine valleys, the overall coverage of the radar visibility above the Alpine ridges is good.

A detour to the shielding problem might be found in another concept for a radar network, for instance the installation of a hundred small low-cost radars. However, considering the effort encountered when searching for a suitable location to install an antenna, this
solution is unrealistic. Composing the observations of hundred radars to a country-wide image needed to be optimized and would allow better observations of precipitation in Alpine valleys. Considering the range-velocity ambiguity problem (Section 1.3), the higher density of radars would lower the range needed and allow for a higher Nyquist velocity. Since the dealiasing is a critical step when processing Doppler velocities, an increased Nyquist velocity is welcome. However, this work shows what wind information can be retrieved from the existing radar network.

Shielding by the orography not only hinders the observation of the reflectivity of precipitation echoes in the mountain valleys, but even more reduces the applicability of multiple-Doppler techniques. In Section 5.1 the dual-Doppler region was derived, where the composition of the observations of two Doppler radars is geometrically possible. If three radars observe a given coordinate, the horizontal wind is over-determined and the least reliable of them can be omitted. An observation can become unreliable because of partial shielding, distant range from the antenna or too much height of the scanned volume.

Figure 6.1 shows the multiple-Doppler regions of selected radar combinations in the SRN for four antenna elevation angles. The dual-Doppler regions with circle-like areas are shown in darker shade. However, the long baseline between the radars leads to long ranges from the radars and often limits the dual-Doppler regions’ extension. This is best notable in the bottom left plot in Figure 6.1 (elevation angle 2.5°). There, the Alps have weak shielding effect and the multiple-Doppler regions are mainly determined by the viewing angles. Dual-Doppler wind vectors can only be retrieved in few regions of Switzerland. A majority of them are located over the Alps at relatively high altitude. We find a small fragment south of Bern with a triple-Doppler region (darkest shade in Figure 6.1). For lower elevation angles (top plots in Figure 6.1) the Alps shield large portions of the Monte Lema, the Albis radar and also parts of the La Dôle radar. Since the multiple-Doppler regions are collocated with the Alps, they vanish quickly along with increased shielding.

In order to enlarge the multiple-Doppler regions in northern Switzerland, the Doppler observations of a foreign radar could be included. The C-band Doppler radar on Feldberg in Germany operated by the German weather service (DWD) is located close to the Swiss border. The Feldberg radar is in a favorable position (indicated with another triangle symbol in the bottom right plot of Figure 6.1) for a dual-Doppler combination with the Albis radar. Its contribution to the dual-Doppler regions is indicated in Figure 6.1. Non-operational tests have already been successfully performed, but administrative and technical barriers have to be overcome to include these observations oper-
Figure 6.1: Geographical overview of the Swiss Radar Network (SRN) showing the visibilities of a multiple-Doppler configuration for various elevation angles. Triangle symbols indicate the position of the three SRN radar antennae on Albis, La Dôle and Monte Lema. The lightly shaded circles mark the regions covered by the radars (assuming ranges up to 130 km). Some regions in the Alps are shielded and appear white in the image. The next darker shade indicates that a dual-Doppler method is geometrically possible. The darkest shade indicates visibility of all three radars.
ationally. Another weather radar weather radar located suitably for multiple-Doppler applications is the research C-band radar of the Swiss Federal Institute of Technology (ETH) in Zürich, installed on Hönggerberg (Appendix B). Its scan strategy is handled on a case-by-case basis allowing for scans matched to the meteorological event. The ETH radar was combined with the MeteoSwiss Albis radar in Chapter 4 for an analysis of the winter storm Lothar. This study demonstrated the high resolution of the wind product for this radar combination. The short baseline between the two radars (13.75 km) on the one hand allows for highly resolved wind information in the dual-Doppler region. On the other hand it renders the dual-Doppler region relatively small compared to the area of Switzerland. Hence, the value for operational purposes is mainly found in a reliable local wind retrieval whose information can improve the wind field in the vicinity through propagation in space.

### 6.2 Initialization of the wind field

This section will outline the work for the operational application of the wind field retrieval, as it is currently tested. The polar PPI data, treated with the procedure outlined in Section 1.4, are provided in real-time (five minute delay) by MeteoSwiss. Beside the PPI images the VAD product is generated from each half-volume scan (2.5 min). The VAD technique was described in Section 1.5 as a technique to determine the average vertical wind profile in the vicinity of a Doppler radar. The VAD products of the three radars are available in real-time to support the operational wind field retrieval algorithm.

At present, the operational product is derived from the 1.5° elevated scans, where the three operational Swiss weather radars can see precipitation. This restriction to limit the analyses to only one elevation is needed since the computing time is limited, however, the algorithm is prepared for including additional scans after the test phase. The 1.5° PPI is known to contain few clutter echoes and good observations after filtering. Figure 6.1 indicates moderate shielding of the 1.5° elevation, whereas for lower elevation angles loss of data is much more important. The wind field retrieved from the higher PPI data yet needs to be handled with care because the altitude of the observations varies more with horizontal position. Figure 6.2 shows cross sections between the three radars with the topography and the PPI scan heights. They indicate that the 1.5° scan is appropriate for balancing the availability of the data (shielding) and the need for low altitude. Along the profile the radar beams intersect at ranges of around 100 km at heights of 4 to 5 km. This and the maximum range for Doppler velocity observations of 130 km (Table 6.2) determine that wind fields retrieved from the 1.5° PPI scans are at
6.2. Initialization of the wind field

altitudes between 1 and 5 km. This has to be considered when interpreting the retrieved wind fields.

![Cross sections along the baselines of two of the three Swiss weather radars, respectively, showing the topography profile. The 1.5° scan is added for comparison with the topography. The center of the beam is marked with the solid curve, dotted lines indicate the half-power beam width of 1°. The first diagram shows the cross section La Dôle - Albis, the second one La Dôle - Monte Lema and the third one Albis - Monte Lema.](image)

Both, for the dealiasing (Section 2.4.4) and for the initialization of the objective analysis in the wind field retrieval (Section 5.2), an estimate for the environmental wind is helpful.
Therefore, the first task of the operational wind field program is to seek for the best available information about the environmental wind. This wind (profile) is assumed to be representative for the entire wind retrieval domain. The operational algorithm searches a) for a VAD product and b) attempts to run a reflectivity tracking (TREC) with the latest PPI scans to determine a mean vector for the motion of the precipitation system. For convective storm events where the echo structure shows single cells, the tracking is expected to provide a better estimate of the average movement. Because the tracking method bases on a best correlation analysis, the tracking vectors can be investigated for quality (reliability) using the correlation coefficient. A threshold is set in order to decide whether the tracking vector (correlation > threshold) or the VAD profile (correlation < threshold) is used for the environmental wind. For the VAD wind profile each wind vector can be judged for its quality by looking at the expected root-mean-square error (RMSE) or the number of gates (azimuths) included in the analysis. Note that the tracking algorithm does not resolve echoes at different height levels. It is planned to consider radiosounding observations or numerical weather analyses in the future, in order to have additional and independent wind information.

Searching for the best environmental wind from the techniques just mentioned is carried out for each radar separately. For the Monte Lema radar south of the Alps this is especially important since the synoptic situation can cause different large-scale flows. Wherever the environmental wind stems from, the representativity for the locations, where the Doppler velocities are dealiased or the wind vectors are retrieved, needs to be scrutinized. Depending on the meteorological situation the inhomogeneity of the airflow causes disagreement of the local and the environmental wind. Moreover, the elevation of the beam needs to be considered when assigning or comparing the environmental wind to single local wind vectors.

An alternative way to initialize the control variables of the dealiasing and wind field retrieval algorithm is to consider the past, i.e., a previously retrieved wind field. From these, radial velocities and hence the old Nyquist numbers can be estimated for each grid point, to initialize the new Nyquist numbers for the variational dealiasing. The past wind field serves to initialize the wind vectors in the objective analysis of the wind field retrieval. This is supposed not only to improve the reliability of the methods by ‘leading the way’ early in the algorithm, but also to improve the performance of the processing in terms of decreased computing time. Experiments to scrutinize these presumptions are underway.
6.3 Parameters of the wind retrieval program

The wind field retrieval program searches for the latest PPI scans from the three SRN radars. The PPI scans are dealiased by applying the technique presented in Chapter 2 and consulting the environmental wind field determined above. The quality control (Section 2.7) eliminates regions with suspicious Nyquist numbers, such that no wind information will be available at these positions. The dealiasing products as well as the latest reflectivity images and the environmental wind estimate provide the input for the wind field assimilation.

The multiple-Doppler wind field retrieval technique of Protat and Zawadzki (1999) was outlined and investigated for noise filtering in Chapter 3. It combines the Doppler velocity observations of radars where geometrically appropriate to retrieve the three-dimensional wind field. The single-Doppler version of Laroche and Zawadzki (1994), where the former technique stems from, was treated in Section 5.2. It includes reflectivity observations in addition to the Doppler velocity data to replace the missing horizontal (cross-beam) wind component. We conclude from the visibility plots in Figure 6.1 that in general a single-Doppler wind field retrieval technique has to be applied for the Swiss radar network. However, the method should be compliant to render the wind field more reliable where multiple-Doppler vectors can be retrieved using the availability of supplementary observations. The current wind field algorithm, operationally employed in a test platform, is based on a single-Doppler concept as proposed in Section 5.2, but hosts the multiple-Doppler features to be supplied from additional radars’ observations wherever available. Albeit the small area, dual-Doppler wind information can propagate into the neighborhood through the smoothness constraint (Guillemette and Zawadzki 1999, Wüest et al. 1999). The range of this influence is however limited.

The wind field retrieval algorithm provides a wind product with high resolution in space and time. Currently, a 2 km horizontal grid reaching beyond the Swiss borders is chosen for a real-time product every ten minutes. For specific purposes the resolution can be improved till reaching the limitations given by the radar observations. At present, the technique is tested in different meteorological situations and special circumstances such as loss of radar data and network status. Tools are ready to calculate wind fields from volume scans. This requires the transformation to a three-dimensional Cartesian grid (CAPPI). The computational effort is then increased in a non-linear way, requiring the hardware to be upgraded or the (temporal or spatial) resolution to be reduced. For local services as e.g. shear warnings for an airport, the wind product can be optimized. The radar data can be analyzed at high resolution in the vicinity of the place of interest.
This chapter informed about the geographic and technical circumstances for an operational wind field retrieval and its implementation in a test platform. Section 7.3 will discuss several aspects concerning the compliance of the methods of this thesis with an operational framework.
Chapter 7

Conclusions

7.1 Review of the thesis

Five objectives were formulated for this thesis in Section 1.8. In brief they were 1) to develop a reliable technique to dealias the Doppler velocity observations of weather radars, 2) to optimize the filtering of noise in the velocity information derived from radar observations, 3) to take advantage of the latter methods to retrieve the three-dimensional wind field for analyzing important meteorological events like Lothar, 4) to simulate the profit of supplementary wind information in a single-Doppler wind retrieval and 4) to implement the methods for operational use. The introduction in Chapter 1 lists the problems associated with the retrieval of velocity information from Doppler radar data, the content of this thesis.

A dealiasing concept based on variational analysis is proposed in Chapter 2. Taking the human eye as a paragon, the method segments the Doppler velocity image into regions with constant Nyquist number (Section 2.3.2). This segmentation reflects the procedure of an experienced radar meteorologist, but bears a risk for grouping gates of different wind character (bridging). Based on the identified regions, a series of constraints are formulated which require continuity of the Doppler velocity within the Doppler image (Sections 2.3.4 and 2.4.5) and overall agreement with an environmental wind estimate (Section 2.4.4).

Experiments with a simulated PPI have verified the implementation and capability of the dealiasing algorithm to correct Doppler velocity images (Figure 2.10). Advantages of the variational dealiasing technique are that 1) no region or gate is pre-determined to be unfolded (Section 2.4.4), 2) the propagation of errors is reduced by properly weighting the constraint considering the environmental wind (Section 2.4.7) and 3) an estimate
for the quality / reliability of each Nyquist number assigned to a region is made available (Section 2.7).

In order to retrieve the wind field from Doppler radar observations, the method by Protat and Zawadzki (1999) - summarized in Section 3.2 - is adapted and installed for the Swiss technical and natural environment. This method is based on a variational analysis, i.e., it assimilates a model wind field to the radar observations while fulfilling at the same time given physical constraints. Because of the strongly varying Alpine and pre-Alpine topography, a new lower boundary constraint is implemented in Section 3.5.3. It forces the wind component normal to the Earth surface to be zero at the surface level.

Chapter 3 investigates the effect of two concepts to eliminate spurious vectors in the wind field retrieval. The first method smoothes the radar data (data smoothing). It is applied prior to the wind field assimilation. The second method is a smoothness constraint for the wind field model. It minimizes second order spatial derivatives of the wind field. Horizontal wind fields are retrieved from simulated radar observations, using different noise filtering techniques. We find that the smoothness constraint eliminates noise more efficiently than the data smoothing (Figures 3.6 and 3.7). It also helps to retrieve a more accurate wind field. The data smoothing on the other hand improves the convergence rate, but suffers from less accuracy in the retrieved wind vectors (Tables 3.2 and 3.3). Experiments including the retrieval of the vertical wind demonstrate the importance of the smoothness constraint. The latter leads to an accurate three-dimensional wind field and a fast convergence rate, both not possible using the data smoothing alone (Tables 3.4 and 3.5). The data smoothing can eliminate the noise with increasing strength (given by the smoothing parameters) but not without reducing the wind variation. The application of the smoothness constraint without using the data smoothing is recommended. It allows to better detect and quantify wind peaks and to conserve the significant variability of the wind field. This is an important attribute for further application of the wind fields in numerical models (thermodynamic analyses, forecasting).

The winter storm Lothar struck in northern Switzerland on 26 December 1999 and caused severe damages to human beings, installations and forests. Most of these damages happened when a narrow cold-frontal rainband (NCFR) passed around noon (Figure 4.2). The NCFR was scanned with the ETH Hönggerberg and the MeteoSwiss Albis radar, both providing PPI images. The relative position of the NCFR and the two radars allows for a dual-Doppler wind field analysis using the techniques presented in this thesis. The variational dealiasing technique is able to unfold most PPI images automatically, despite of multiple folding of the Doppler velocities (Figure 4.7). The wind...
field retrieval technique proposed by Protat and Zawadzki (1999) is used with the noise filtering settings recommended in Chapter 3. The wind product reveals the convergence line associated with highest reflectivities of the NCFR. The strongest winds are found at the trailing edge of the rainband, i.e. behind, not ahead of the front (Figure 4.9). This is unusual for an NCFR and in contrast to earlier studies of NCFRs (Wakimoto and Bosart 2000). Wind peaks are also detected behind the core regions of the NCFR. According to Schmid et al. (2001) the damage pattern in the Swiss forests shows a W-E orientation of parallel bands, a few tens of kilometers apart. The positions of the core regions - and hence the maximum winds - are well correlated with the damage. The application of the dealiasing and the wind field retrieval technique demonstrate the value and the ability to derive highly resolved wind fields with Doppler radar.

No Doppler radar networks are dense enough to provide areal coverage with multiple-Doppler capabilities. In the first place the precipitation system must be in the vicinity of one radar. In addition, the geometrical aspects of multiple-Doppler applications require an appropriate viewing angle to the antennae (Section 5.1). For radar range-wide retrieval of the wind field, the methods need to cope with the observations from a single Doppler radar. In Chapter 5 a version of the wind field retrieval algorithm by Protat and Zawadzki (1999) is applied to investigate single-Doppler and multiple-Doppler capabilities. This allows to quantify the reliability of single-Doppler wind field retrievals using dual-Doppler retrievals as a reference. Case studies for various meteorological situations are described using the ETH Hönggerberg and the MeteoSwiss Albis radar. To scrutinize the profit of supplementary wind field information from any additional source, the resolution of data from the second radar is artificially reduced to simulate both punctual and volume-averaged observations (Figure 5.4). An error analysis for the cross-beam wind component of the first radar in Figure 5.8 reveals that even sparse supplementary wind field information improves the accuracy of the wind product, whereas punctual information is less representative and hence less helpful compared to volume-averaged observations. When retrieving the wind field from a single Doppler radar without or with punctual supplementary wind information, the initialization of the model wind field (which is assimilated) plays an important role. The errors in the tangential wind component found when retrieving the wind field from a single Doppler radar with and without a reliable initialization, and with varying availability of supplementary wind information are shown in Figure 5.8.

The Swiss weather radar network consists of three C-band Doppler radars covering most of the country (Figure 6.1). It belongs to the densest networks worldwide. The visibility of the radars in combination with geometrical requirements for multiple-Doppler applications indicate that in general a single-Doppler method needs to be applied. Dual-
Doppler vectors can be retrieved only in few regions in Switzerland. On an experimental basis, the methods and findings of this thesis are implemented to retrieve the wind field in real-time. Chapter 6 summarizes the operational procedure based on a single-Doppler wind field retrieval. Supplementary wind field information from other observations can improve the accuracy/reliability. Some thoughts about the operational application are given in Section 7.3.

7.2 A combined variational analysis

The dealiasing approach in Chapter 2 and the wind field retrieval algorithm in Chapter 3 are both based on variational techniques. This fact may suggest the question as to whether the variational techniques of the two procedures can be combined. Both methods constrain their objective analysis with equations based on the Doppler velocity and there is a common goal, i.e., to retrieve wind information. A combined method to dealias Doppler velocities and to retrieve the two- or three-dimensional wind field in a single variational analysis could be more elegant and efficient at first. A single minimization procedure might reduce the computing time. However, we recited to melt the dealiasing technique with the variational wind field retrieval method. The two tasks are carried out individually and sequentially for the following reasons:

- The aliasing induces a systematic error to the measurements of the Doppler velocity. This error should be corrected before interpreting the data. This chronology is as to say prescribed, but likely to be ignored by a combined variational technique.

- Dealiasing the vast amount of observations is a critical point within the entire wind field retrieval. Albeit sophisticated methods can be figured out, a risk for relics remains and needs to be accounted for. A quality control for the dealiased radial velocities must be applied between the dealiasing and the retrieval of the wind vectors.

- In a combined method, the Cartesian wind components were to be assimilated to observations which themselves are still being altered. The Cartesian components would depend on both the Doppler velocities and on the associated Nyquist number. The convergence of the assimilation is expected to be lower in the combined case, since competition between the constraints can arise.
7.3. Operational application

NYquist numbers were defined to be integer values in (2.1). Section 2.4.8 described how the calculated real Nyquist numbers are rounded to integer values conform with their definition. Along with a combined variational analysis, the latter step is not feasible in the same manner and we do not know about an alternative numerical solution for this problem.

7.3 Operational application

Today, in the operational software of the Swiss radar network, the Doppler velocity observations are just used to eliminate clutter and to produce a processed VAD product, providing a vertical wind profile hopefully representative for the vicinity of the radar antenna. Wind field retrieval techniques like the one presented by Protat and Zawadzki (1999) allow to derive the three-dimensional wind field at the resolution of radar observations. Such wind products may help to analyze the development and thermodynamics of precipitation systems. In an operational environment, alerts for critically strong wind speeds, wind shear and microbursts may be based on the wind retrieval product and enhance flight safety. Numerical weather forecast models can be initialized with Doppler radar-derived wind fields. This initialization is currently investigated by the COST-717 committee (Lindskog 2000).

This thesis presents various aspects and methods to retrieve the wind field from Doppler radar data. Issues related to their meaning in an operational environment are discussed. For the entire processing of the wind information, a pre-filtering by the radar computer is helpful: all cluttered observations are filtered without eliminating true zero velocity observations where the tangential velocity is minimal, and isolated pixels (speckle data) are eliminated, being of minor value for the wind field. Section 2.3.1 presents a three-step filter to erase observations of the latter type. The early application of these filters accelerates subsequent algorithms including the dealiasing. Often in the data of the Swiss radar network ‘clear air echoes’ are observed in the vicinity of the radar antenna. The clutter filtering scheme by Joss et al. (1998) preserves these values, allowing to retrieve the wind field also in non-precipitation situations.

When the dealiasing algorithm was proposed in Chapter 2, as well as in Chapter 5 where the wind field retrieval was investigated for a single Doppler radar, it became evident that a reliable estimate of the environmental wind is of importance, i.e. the background wind field. Although the dealiasing algorithm can force continuity in a Doppler velocity image without using a constraint for the environmental wind (Section 2.4.4), the
latter substitutes the correction and reduces the propagation of errors. When retrieving the wind field from a single Doppler radar, the initialization of the wind field with the background information raises significantly the accuracy of the product. A reliable and representative estimate is required, whether this product stems from a VAD/VVP, a tracking technique for radar or satellite data, a radiosounding, numerical models, earlier wind retrievals or other sources. The wind field retrieval might rather be paused when for some reason the availability of this estimate is interrupted, and resumed on recovery of the problem. With the introduction of the quality estimate for each dealiased region in the Doppler velocity image, suspicious radial velocities are marked and can be filtered, using the residuum between integer and calculated Nyquist numbers. Applying the dealiasing operationally should imply that suspicious values are omitted for the wind field retrieval. Whereas archived case studies can be manually corrected, the operational product is restricted to the observations determined reliable. For the operational application, the criteria for filtering erroneously dealiased values can be strengthened, e.g., radial velocities deviating strongly from the background wind field can be marked suspicious. The wind field retrieval algorithm relies on the success of the dealiasing procedure. In the retrieval concept, values passing the dealiasing procedure are considered valid and serve for the data assimilation. The noise filtering scheme recommended in Section 3.6 improves both the accuracy as well as the performance of the wind retrieval algorithm in terms of computing time. The current implementation is written in the IDL language. The 1.5° PPI can be dealiased and processed every five minutes, i.e., the time interval at which volume scans are repeated, to form a wind field product as outlined in Chapter 6. This is carried out on a workstation, on which a version compiled in a lower-level programming language should accelerate the process by a factor of two to five (personal estimate), as compared to the IDL-software used in the present experimental environment.

### 7.4 Outlook

The implementation of the dealiasing and wind field retrieval program currently serves as a test platform. Plans for the future include the following development:

- The variational dealiasing technique may be extended to four dimensions. Currently, two-dimensional PPI images are corrected using the Nyquist numbers of a previous PPI as initialization of the objective analysis. The temporal dependency could be included as an additional constraint in the variational model to increase
its influence. The fourth, vertical dimension could be considered by dealiasing volume scans from the highest elevation down to the lowest, always using the results from the next higher elevation. Because of reduced clutter at high elevations, this procedure might lead to an improved efficiency.

- It was mentioned in Section 6.1 that foreign weather radars close to the Swiss borders can provide supplementary Doppler velocity observations. These can be included to enlarge the multiple-Doppler regions in Switzerland. Case studies have already been performed with the Feldberg C-band radar (Figure 6.1) of the DWD (German weather service).

- The wind field of the NCFR in the winter storm *Lothar* was successfully retrieved with the presented methods. Because of the high interest indicated by (re-)insurances, forestrial institutes and the public, this storm will be further investigated. Wind fields at different states of the storm will be retrieved and correlated with the damage pattern. Further storms and precipitation systems will be analyzed. The retrieval of thermodynamics is anticipated, following the concept of Gal-Chen (1978).
# Appendix A

## Variables

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<th>Description</th>
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<td>$i, j$</td>
<td>indices in an array</td>
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</tr>
<tr>
<td>$J$</td>
<td>cost of a constraint</td>
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</tr>
<tr>
<td>$n$</td>
<td>Nyquist number</td>
<td>1</td>
</tr>
<tr>
<td>$s$</td>
<td>factor to reduce the resolution of wind information</td>
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</tr>
<tr>
<td>$r(i, j)$</td>
<td>region index</td>
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<tr>
<td>$t$</td>
<td>time</td>
<td>s</td>
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<td>$v_a$</td>
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<td>$v_M$</td>
<td>measured Doppler velocity</td>
<td>m/s</td>
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<td>$v_t$</td>
<td>terminal fall velocity of precipitation particles</td>
<td>m/s</td>
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<tr>
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<td>velocity in the direction of $\vec{x}$</td>
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<td>$w$</td>
<td>weight factor</td>
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<td>$\vec{x} = (x, y, z)$</td>
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<td>m</td>
</tr>
<tr>
<td>$\epsilon_{cb}$</td>
<td>root mean square error (RMSE) in the cross-beam wind component</td>
<td>m/s</td>
</tr>
<tr>
<td>$\eta$</td>
<td>radar reflectivity, usually given in dbZ, i.e., $10\cdot \log(\eta/\eta_0)$</td>
<td>mm$^6$/m$^3$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>air density</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>vertical vorticity</td>
<td>1/s</td>
</tr>
</tbody>
</table>
Appendix B

Specifications of the ETH radar

The specifications of the ETH C-band Doppler radar on H"onggerberg are listed in the following table. The radar is operated for research purposes on a case-by-case basis. For this purpose some parameters as the pulse repetition frequency (PRF) can be altered. The table lists the parameters as they were set for the studies in this thesis.

Table B.1: Specifications of the ETH Doppler weather radar on H"onggerberg.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>antenna diameter</td>
<td>2.5 m</td>
</tr>
<tr>
<td>beam width</td>
<td>1.65°</td>
</tr>
<tr>
<td>gain</td>
<td>40 dB</td>
</tr>
<tr>
<td>peak power</td>
<td>280 kW</td>
</tr>
<tr>
<td>frequency</td>
<td>5.62 GHz</td>
</tr>
<tr>
<td>wavelength</td>
<td>5.33 cm</td>
</tr>
<tr>
<td>pulse repetition frequency (PRF)</td>
<td>1200 Hz</td>
</tr>
<tr>
<td>pulse-width</td>
<td>0.5 μs</td>
</tr>
<tr>
<td>min. det. signal 100 km</td>
<td>12.7 dBZ</td>
</tr>
<tr>
<td>Swiss coordinate East</td>
<td>680.930 km</td>
</tr>
<tr>
<td>Swiss coordinate North</td>
<td>251.340 km</td>
</tr>
<tr>
<td>longitude</td>
<td>8.512°</td>
</tr>
<tr>
<td>latitude</td>
<td>47.408°</td>
</tr>
</tbody>
</table>
Bibliography


Curriculum vitae

Marc Alexander Wüest
born on 20 December 1973 in Zürich, Switzerland

Education and Work

Aug 1999 - Nov 1999  Maintenance of the measuring site in Macugnaga, Italy for the Mesoscale Alpine Programme (MAP)


Oct 1998 - Sep 2001  Ph.D. student at the Swiss Federal Institute of Technology (ETH) Zürich, Institute for Atmospheric and Climate Science

May 1998 - Sep 1998  Scientific researcher at the Swiss Federal Institute of Technology (ETH) Zürich, Institute for Atmospheric and Climate Science

Investigation of different beam configurations for wind profilers

Apr 1998  Willi Studer award for best graduation exams in Earth Sciences at ETH Zürich

Apr 1998  Diploma thesis at the Institute for Atmospheric and Climate Science, ETH Zürich: Validation of a single-Doppler variational analysis technique with a dual-Doppler wind retrieval method. Under the guidance of Prof. A. Waldvogel

Aug 1996 - Sep 1996  Max-Planck Institut für Meteorologie, Hamburg, Germany

NCEP reanalysis of the runoff of the Parana River.

Sep 1996 - Nov 1996  Amt für Gewässerschutz und Wasserbau des Kantons Zürich, Switzerland

Parameterization of the Q347 (“dry weather”) runoff.

Oct 1993 - Apr 1998  Student of Earth Sciences at Swiss Federal Institute of Technology (ETH) Zürich

1986 - 1993  Gymnasium in Zug, Switzerland: Matura type B

Willi Beusch award for best graduation

1980 - 1986  Primary school in Steinhausen, Switzerland
**Teaching**

Oct 2001 - Feb 2002 Lectures in *Atmospheric Physics I and III* at ETH Zürich

Oct 1998 - Sep 2001 Excercises in Remote Sensing at ETH Zürich, Switzerland

May 2000 - Jun 2000 Courses in *Internet Basics* at Kaufmännische Berufschule, Zug, Switzerland

**International Conferences**

July 2001 30th Conference on Radar Meteorology, Munich, Germany

September 2000 1st European Conference on Radar Meteorology, Bologna, Italy

August 2000 13th International Conference on Clouds and Precipitation, Reno, USA

July 1999 29th Conference on Radar Meteorology, Montreal, Canada

June 1999 MAP Meeting, Appenzell, Switzerland

March 1998 COST-75 Final International Seminar on 'Advanced Weather Radar Systems', Locarno, Switzerland
List of publications


I address my thank to Dr. Jürg Joss for the intensive discussions he lead with me, the critical review of my work and the worthy challenges issued. I thank Dr. Willi Schmid, Prof. Hans Richner and Prof. Huw Davies for their engagement and cooperation in both scientific questions and other situations, and whenever needed.

Prof. Isztar Zawadzki, Prof. Frederic Fabry, Alain Caya, Ramon de Elia and Pascal Guillemette from the Atmospheric Sciences at McGill University in Montreal, Quebec, received me with trust and helped me to understand and appreciate their work. I thank them for the big time stay in Montreal and the excellent support during and after it.

Though not appropriately represented in this thesis, I spent many months of my time as a PhD student on field campaigns for AMDOP near Zürich and for MAP in Italy. These campaigns are counted among the most fascinating and instructive periods of my education and I am grateful to all people involved in enabling me the participation. Volker Erbert was the ideal partner for these operations and numerous salutary conversations.

I appreciate the repeated and productive involvement of Urs Germann in my work. Gianmario Galli indicated on-going interest in my proceedings and satisfied all my needs concerning observational data and information on the radar instruments.

Congratulations go to Eszter Barthazy, heading our research group under difficult circumstances and to the entire Institute for Atmospheric and Climate Science (IACETH) including my fellow PhD students. Responsible for the pleasant atmosphere and good organization at our Institute and in our research group are many people, amongst them Rudolf Lüthi, Eva Choffat, Hans Hirter and Peter Isler.

I would like to express my gratitude to my friends for giving me good compensation from school and work and letting me solve related sorrows.

I send my most cordial thanks and best wishes to my family for being so faithful and having enabled me the life I lead.

I thank God for always accompanying me and giving me the health to do good.