Three-dimensional mapping of fine structure in the solar atmosphere –

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Cover image: The left side is a false color image of a sunspot as observed in the pseudo continuum between the Ca\,\textsc{ii} K and Ca\,\textsc{ii} H lines at \(\sim 395.4\) nm. The right side shows the pixels where the temperature gradient is low in color where the color codes the total circular polarization level. Both images are aligned to form the whole sunspot.
Abstract

The effects on image formation through a tilted interference filter in a converging beam are investigated and an adequate compensation procedure is established. A method that compensates for small-scale seeing distortions is also developed with the aim of co-aligning non-simultaneous solar images from different passbands. These techniques are applied to data acquired with a narrow tiltable filter at the Swedish 1-meter Solar Telescope. Tilting provides a way to scan the wing of the Ca\textsc{ii} H line. The resulting images are used to map the temperature stratification and vertical temperature gradients in a solar active region containing a sunspot at a resolution approaching 0\textquoteleft 10. The data are compared with hydro-dynamical quiet sun models and magneto-hydrodynamic models of plage. The comparison gives credence to the observational techniques, the analysis methods, and the simulations. Vertical temperature gradients are lower in magnetic structures than in non-magnetic.

Line-of-sight velocities and magnetic field properties in the penumbra of the same sunspot are estimated using the CRISP imaging spectropolarimeter and straylight compensation adequate for the data. These reveal a pattern of upflows and downflows throughout the entire penumbra including the interior penumbra. A correlation with intensity positively identifies these flows as convective in origin. The vertical convective signatures are observed everywhere, but the horizontal Evershed flow is observed to be confined to areas of nearly horizontal magnetic field.

The relation between temperature gradient and total circular polarization in magnetically sensitive lines is investigated in different structures of the penumbra. Penumbral dark cores are prominent in total circular polarization and temperature gradient maps. These become longer and more contiguous with increasing height. Dark fibril structures over bright regions are observed in the Ca\textsc{ii} H line core, above both the umbra and penumbra.
A Maria de Carmo e Luís Paulo
List of Papers

The following papers, referred to in the text by their Roman numerals, are included in this thesis.

PAPER I: A tilted interference filter in a converging beam
DOI: 10.1051/0004-6361/201117305

PAPER II: Three-dimensional temperature mapping of solar photospheric fine structure using Ca II H filtergrams
DOI: 10.1051/0004-6361/201220344

PAPER III: Ca II H sunspot tomography from the photosphere to the chromosphere

PAPER IV: Detection of Convective Downflows in a Sunspot Penumbra
DOI: 10.1126/science.1206429
Includes Supplementary Online Material (SOM)

PAPER V: SST/CRISP observations of convective flows in a sunspot penumbra
DOI: 10.1051/0004-6361/201118026

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The following publications of the author are not included in this thesis.

- **Inovação e Interdisciplinaridade nos Currículos do IST**  

- **Temperature structure from Ca II H wing inversions**  

- **Temperature stratification in the Sun’s photosphere in high horizontal resolution using Ca II H filtergrams**  

- **Photospheric Temperatures from Ca II H**  
  DOI: [10.1007/978-3-642-02859-5_74](https://doi.org/10.1007/978-3-642-02859-5_74)

- **The connection between convective downflows and spines in a sunspot penumbra**  
Author’s contribution to the papers

Below I briefly account for my contribution to the papers where I am not single author.

**Paper I**: Participated in the development of the methods and was responsible for the tests on real data. Contributed to text and figures.

**Paper III**: Made the observations, reduced the data and wrote the first complete version including figures.

**Paper IV**: Made the observations, developed the reduction scheme, made the reductions. Worked on the analysis. Contributed to text.

**Paper V**: Made the observations, developed the reduction scheme (for high fidelity full Stokes polarimetry), and made part of the data reductions.
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**Sammanfattning**

**Acknowledgements**

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1. Introduction to the solar atmosphere

1.1 Overview

The Sun is not a bland glowing uniform orb. Its atmosphere is a place of extremes by Earth standards and has its own characteristic landscapes. It is a scene of furious struggles between kilo-Gauss magnetic fields spanning enormous scales, pushed away by and partially inhibiting vigorous convection, forming sunspots (see Fig. 1.2) that are often the size of the Earth or larger. The effects of subsurface convection otherwise dominate the bright solar surface, forming a granulation pattern (see Fig. 1.1 for an extremely well resolved granulation image) and pushing the smaller field concentrations to its boundaries. There the small-scale concentrated magnetic field contains gas of lower density forming optical “holes” in the surface. These show us a hotter deeper layer and are thus called bright points (see upper right corner of Fig. 1.1). At disk center these are always located at or adjacent to inter-granular lanes, where the cold down-flowing gas makes them look darker than the up-flowing hot gas at the center of the granules. Below the inter-granular lanes, the down-flowing gas becomes turbulent, emitting sound and exciting oscillations that make the entire Sun vibrate like a giant bell.

These structures characterize the deep photosphere. In the upper photosphere the granulation pattern gives way to reversed granulation (see Fig. 4.4). Progressing upwards we have the chromosphere, perhaps best defined as all the filamentary stuff that one sees just above the solar surface during an eclipse. It is an environment where, unlike in the photosphere, magnetic field pressure dominates over the gas pressure almost everywhere and thus the observable structures form beautiful canopies of fibrils like the ones visible in Fig. 4.5 (a quite remarkable image) and large, dark, filaments.

The majestic canopies of magnetic fields above the solar photosphere, when twisted by the movements at their foot-points, will often find that they can exist in a lower energy state if they reconnect to form new loop configurations. This leads to the powerful flares that light up the canopy and bathe the upper atmosphere of the Earth in X-rays. Occasionally, the new reconfigured magnetic field frees plasma that expand to sizes larger than the Sun and
accelerate outwards into the solar system. These are known as coronal mass ejections and sometimes hit the Earth giving us wonderful auroras and a few headaches to controllers of satellites and power grids.

The subject of this thesis is the development and testing of observational techniques that help us analyze the physical properties of these phenomena. The most important application will be sunspots and therefore we will look further into these structures in this introduction.

1.2 The mysterious penumbra of sunspots

As visible in Fig. 1 of Paper II (an image at the top of the resolution possible in today’s telescopes), a sunspot is composed by two distinct parts: the dark umbra that, in the observations of this thesis, has an intensity of only 16% of the mean granulation intensity of the quiet/ordinary photosphere\(^1\) and

\[^1\text{In the continuum near 538 nm.}\]
a penumbra, composed by complex filamentary structure with dark and bright filaments. The bright penumbral filaments, especially when observed in the inner portion (close to the umbra) and when seen at high resolution, have slim dark cores ([Scharmer et al.](2002)). A sunspot’s umbra is dark because convection is partially inhibited by the strong magnetic field. But what about the penumbra? It is actually quite bright at over 70% of the granulation average intensity. And why does it have a filamentary appearance at all?

The key to answering these questions is in the flow dynamics of the penumbra. It all starts with a 104-year old observation by John [Evershed](1909) where strong \((\sim 2\ \text{km s}^{-1})\), ubiquitous, and radially oriented outflows were detected in the penumbra of sunspots. In fact we can characterize the different penumbral models based on their explanation of this flow structure (and do so in the following subsections).

### 1.3 Flux tube based models

Most models assume some combination of magnetic-field-dominated structures, flux tubes, extending from the umbral boundary to the outer penumbra. In siphon flow models, of which the initial formulation was by [Meyer & Schmidt](1968) with a more recent version by [Thomas & Montesinos](1997), the gas flow pattern is radial and vertical and directed along the flux tubes. It is driven by a difference of magnetic field strength between the footpoints of flux tubes at the inner and outer penumbra. In the “uncombed penumbra model”, ([Solanki & Montavon](1993)) horizontal flux tubes carry the Evershed flow, similarly to the siphon models, against a more vertical background field. This model explained broadband circular polarization, first observed by [Illing et al.](1974b), and its center-to-limb variation ([Illing et al.](1974a), [Sanchez Almeida & Lites](1992)).

Other flux tube models, like the hot rising flux tube model of [Schlichenmaier](2002), address weaknesses of the siphon model such as the origin of the gas-pressure gradients driving the radial outflow. It also reproduces the observed inward migration of penumbral grains (for an example of such migration see the \(\sim 0'.10\) resolution movie generated with data acquired for this thesis ([Henriques](2011))). In this model, 1-dimensional flux tubes develop waves and dive up and down out of the observable surface like a sea serpent. As for the other flux tube based models, the flow pattern is always radially and vertically oriented along the filaments.
1.4 The convective gap model

A completely different class of penumbral models, not based on flows along flux tubes, is the convective gap penumbra model of Scharmer & Spruit (2006). There the penumbral filaments are constituted by alternating areas with strong vertical magnetic field and gaps with strongly reduced field strength, where convection pushes the field aside. Convection in the gaps has both a radial flow component and a transversal component (transversal to the orientation of the filaments).
1.5 Simulations

Hydro-dynamic (HD) and magneto-hydrodynamic (MHD) simulations reproduce extremely well other solar features such as granulation ([Stein & Nordlund, 1998], faculae [Carlsson et al., 2004; Keller et al., 2004] and umbral dots [Nordlund & Stein, 1990; Schüssler & Vögler, 2006]). The missing piece of the puzzle to match simulations and observations was until recently the RMS intensity contrast of the granulation, but that discrepancy goes away when compensating for the degrading effects of the telescope (see, e.g., Wedemeyer-Böhm & Rouppe van der Voort, 2009). Simulations of such a well understood and ubiquitous feature as granulation can be used to calibrate observed Doppler velocities (de la Cruz Rodríguez et al., 2011).

Sunspot MHD simulations are not yet perfect, especially when attempting to reproduce the penumbra, but impressive progress as been made in the last years. Heinemann et al. (2007) use a modified version of the PENCIL code (Brandenburg & Dobler, 2002) to simulate a rectangular slice of a sunspot where dark-cored convective gaps are seen migrating inwards into the umbra, similarly to what is observed in time series such as that of Henriques (2011). The same simulation is used again by Scharmer et al. (2008b) who find that the strong radial flow observed in such simulation corresponds to the Evershed flow, which must be explained as the horizontal component of penumbral convection. More recently, Rempel (2011) simulates a sunspot with circular symmetry. Rempel finds that the horizontal flows cannot easily be identified with magnetic flux tubes and that magnetic field-line connectivity is established primarily as a consequence of the flows and not the other way around. He draws a picture where downflows occur throughout his entire simulated penumbra.

1.6 The “clincher”: Measuring the flows

Scharmer (2009) pointed out that the magnetic-field configuration of the flux tube and convective gap models are very similar, and that the main observable difference between these models is the flow pattern. And, of the flow pattern, the most critical and difficult to observe is the presence or absence of downflows at the sides of the filaments and that should be present also in the interior penumbra.

Not surprisingly a considerable effort has gone into trying to measure the flow pattern and, specifically, look for downflows. These have been observed many times but always at the outer penumbra or in a few filament heads around the umbra. For example, Schlichenmaier & Schmidt (1999) and Schmidt & Schlichenmaier (2000) observe downflows in the outer penumbra which have a relatively shallow inclination: −7° from the horizontal. Schlichenmaier &
Schmidt (1999) observe also upflows in the inner penumbra and conclude that these carry enough energy to explain the relative brightness of the penumbra. Franz & Schlichenmaier (2009) measure the flows in a very symmetric sunspot’s penumbra and find upflows in the inner penumbra and downflows only in the outer part of the penumbra and at the tips of filaments, consistent with flow pattern predicted by flux tube based models introduced in the previous section. As recently as 2011, Franz (2011) found no evidence of downflows in the interior penumbra.

In the quest for flow patterns other than the Evershed flow not all observers focused on Doppler signals. Another tell–tale of convection is the apparent motions of filaments and their striations. Ichimoto et al. (2007) observed twisting apparent motions in time-series of penumbral filaments in a sunspot observed far from disk center. Zakharov et al. (2008) observed similar twisting motions in higher resolution using the SST and interpret them as convective rolls. As an alternative interpretation, waves have been proposed as the source for these apparent motions (Bharti et al., 2012).

In Paper IV and Paper V of this thesis, a ubiquitous downflow-upflow pattern, clearly establishing a transversal convective flow pattern, is measured throughout the entire penumbra. The high resolution possible at the SST, combined with observations made in stable and excellent seeing conditions, as well as straylight correction, were the key to obtaining these measurements as the dominant upflow profiles, being brighter, strongly blueshifted, and occupying a wider area, partially mask the darker downflow profiles. Downflows were also measured in a collection of penumbral filaments by Joshi et al. (2011a,b) who used the same shape for the straylight PSF as Paper IV.

1.7 Temperature

Measurements of gas flows are not the only quantities we need to understand the structure and dynamics in the solar atmosphere. Finding the temperature stratification in the solar atmospheric structures is of course central. A large fraction of this thesis (see papers I, II, and III) is devoted to developing and using methods for mapping the temperature in three dimensions in high resolution using filtergrams acquired in the wings of the Ca II H line following Shine & Linsky (1974) and Rouppe van der Voort (2002).

The basic observational methods used are described in Section 2. One of the main new image-treatment techniques that had to be developed for the pur-
pose is described in Section 3. The method for converting observed intensities to temperature is discussed in Section 4.
2. Observing the Sun with the Swedish 1-meter Solar Telescope

2.1 Seeing

Seeing, in the broadest sense, is the collection of distortion and smearing effects caused by the turbulent layers in the Earth’s atmosphere when observing an astronomical object. The turbulence has many different-sized eddies or swirls carrying air with different temperatures and therefore different speeds of light, as usually expressed with the refractive index. Thus these eddies have optical power and can refract the light. To model this effect, the light waves from a distant object are commonly described as a sequence of parallel planes connecting all the points of the emitted light that have the same phase, thus giving us planar wavefronts. When passing through the turbulent air mass, different parts of the wavefront will be delayed by different amounts. The corresponding effects on the wavefronts can be described as a combination of wavefront tilt and corrugation. When observing with a telescope, the entire wavefront will then not arrive at the same time to the telescope pupil, this appears in mathematical descriptions as a change in the phase\(^1\). Because of the wavefront tilt, a point source will appear to come from a different location and therefore be shifted on the detector. Because of the corrugation, the entire wavefront will not interfere constructively in one point, which makes the image smeared and have lower contrast.

Atmospheric turbulence, and thus seeing, varies temporally with a timescale of milliseconds. The longer the exposure time, the more different wavefronts we will see, and therefore integrate in our detector over many different kinds of smearing, resulting in more image smearing. In night time observing exposure times are measured in minutes. In daytime observations we are cursed with stronger turbulence but, with the abundance of photons from the Sun, integration times can often be kept very short. For example, all the blue data for this thesis were acquired with an 8 ms integration time.

Different parts of the detector are looking at different parts of the Sun. The different lines of sight will pass through different parts of the atmosphere

\(^1\) And amplitude as a secondary effect.
and therefore experience different wavefront aberrations. This effect, known as *anisoplanatism*, causes spatial variations in the image degradation. The blurring varies over the field of view and there are geometrical distortions of the image caused by variations in the wavefront tilt.

### 2.2 The Swedish 1-meter Solar Telescope

![Figure 2.1: The Swedish 1-meter Solar Telescope after a hard day of observations with the tower and the gentle northern La Palma slope fully visible. On the far left side of the picture one can see the structure of the Dutch Open Telescope (Rutten et al., 2004), hovering above the ground on thin pillars lifting the telescope up into the northern breeze.](image)

The Swedish 1-meter Solar Telescope (SST; [Scharmer et al., 2003](#)) is designed for high-resolution observations of the solar photosphere and chromosphere. The tower visible in Fig. 2.1 hides a vacuum tube over which a thick fused silica lens of one meter diameter converges the solar light, forming an image at its base. The lens doubles as the main imaging element and as the vacuum seal. The vacuum is usually set to under five millibars by vacuum pumps. The beam carries 700 W of heat from the 1-meter lens and the vacuum prevents it from generating convective swirls inside the telescope, that would destroy the image quality (similarly to what the atmospheric seeing does). The primary lens forms an 18-cm-diameter image of the solar disk, only a small
2.2 The Swedish 1-meter Solar Telescope

portion of which passes through a window in the bottom plate into the optics room, to be used by the observer.

The top of the telescope, known as the turret, was designed to be rigid under wind speeds above $15 \text{ m s}^{-1}$ while projecting the lens into the wind, away from ground turbulence and the building itself, providing cooling to the lens itself at the same time. This design maximizes the benefits from the special wind characteristics of La Palma where often a steady northerly wind will blow along the mountain slope of the island, creating a dynamic layer that is more homogeneous than what the free convection from the heated soil would be otherwise.

The doubling of functions of the main 1-meter lens is paradigmatic at the SST, which is designed to reduce the number of optical components to a minimum. The more optics you have in a telescope the more straylight you are likely to have, contaminating your science data and removing photons from your beam. Also in the spirit of reducing the number of optical elements the telescope possesses no de-rotation optics. The alt-azimuth mount of the telescope means the solar image will rotate when seen in the optics table. De-rotation optics provide only minimal benefits as de-rotation can be performed in software and is not necessary for science from short time periods (as is the case of the data used in this thesis).

After the bottom vacuum seal the beam encounters a tiltable mirror (tip-tilt mirror) and a deformable mirror with 37 electrodes provides Adaptive Optics (AO [Scharmer et al., 2003]), that is, optics that will deform to compensate for the seeing effects. An array of micro-lenses known as a Shack-Hartmann sensor, form sub-pupils that sample different parts of the telescope pupil and creates one image per lens. The images formed by each micro-lens are shifted by amounts that are proportional to the local wavefront tilt within each sub-pupil, thus converting the seeing-induced phase gradients to geometrical shifts. These shifts can then be measured very fast using cross-correlation techniques (very similarly to what is described in Section 2.7). With that phase information the AO mirror can be told to deform in such a way that it will reflect the light into a more planar wavefront. The shape of the compensation is similar to what can be done with various post-processing techniques (MOMFBD in this thesis) but in hardware, in real time, and only up to a certain level of correction restricted by the amount of electrodes and lenslets. The tip-tilt mirror is controlled by the correlation tracker.

Over ten years after its first one-meter-aperture diffraction-limited image the 22 of May 2002, which led to the immediate discovery of penumbral dark cores (Scharmer et al., 2002), the SST continues to provide ground breaking

1 At the time of writing, this is being upgraded to 85 electrodes.
observational data due to this robust design and constant improvement of the software and hardware. Just recently SST data was used for two publications in the two most high-impact science publications worldwide: Nature and Science. These are Paper IV from this thesis and the paper on the discovery of “magnetic tornadoes” by Wedemeyer-Böhm et al. (2012).

2.3 Blue Tower

The “blue tower” is constituted by a vertical assembly of three cameras and the tiltable filter assembly. From the AO, the first optical element of the setup the beam “sees” is a 50/50 beam splitter, sending half of the light to the tiltable filter and the other half to the remaining three cameras. This means that the tiltable filter gets most of the light of all cameras, which enables the best possible signal to noise for line-core images like the one shown in Fig. 4.5. Then another beam splitter sends half of the light upwards and half to the back of the tower setup (the left-most camera in Fig. 2.3). The latter position, since it receives 25% of the total light, is the place for another line-core filter such as a Ca ii K core filter or a line wing filter like the one used in Paper III. Before the last beam splitter, an interference filter selecting the near continuum between the Ca ii K and H lines is placed, with a full width half maximum of 1 nm. The two remaining cameras thus image wideband but one is defocused by about 7 mm to give phase diversity information to MOMFBD.

All the cameras used are MegaPlus II es4020 CCD cameras with a 10-bit digital output. The camera used for phase diversity in this thesis had a non-linear gain factor for one of the halves. A software correction for this, measured by Dr. Sütterlin, was coded into MOMFBD for Paper II and Paper III. The camera has since been repaired.

The most important filter in this setup and for this thesis is the tiltable filter (TF in Fig. 2.2). It’s central passband wavelength is just red-wards of the Ca ii H line-core. It is mounted on a rotation stage controlled by the camera software. Small rotation angles (up to 6°4 in this thesis) change the cavity dimensions of the filter and shift the passband to the blue. This provides an inexpensive way to scan the whole Ca ii H blue wing and is used in the first three papers of this thesis.

2.4 CRISP Imaging Spectro-Polarimeter

The main components of the CRisp Imaging Spectro-Polarimeter (CRISP; Scharmer, 2006; Scharmer et al., 2008a) are a double-etalon Fabry-Pérot interferometer (dual FPI in Fig. 2.2) and two fast-response liquid-crystal polarizers
Figure 2.2: Full Imaging Setup showing both CRISP and the blue tower. Elements in order are, TM: tip-tilt mirror; DM: deformable mirror; RL: re-imaging lens; DC: dichroic beam-splitter; CT: correlation tracker; TF: tiltable filter camera used in Papers I, II, and III; WF: fixed wing filter camera; WB: wideband camera; PD: wideband phase diversity camera. Scheme by Mats Löfdahl.

(LCs in Fig. 2.2). The first etalon has passbands with a full-width half maximum of 60 mA at 6302 Å. The wider passband of the second etalon selects one of the periodic narrower passbands of the second etalon. With an appropriate pre-filter, all other transmission peaks are virtually eliminated. The setup is mounted in a telecentric beam to maximize image quality (Scharmer, 2006). The liquid crystal retarders are identical and have their fast axes at 0° and 45°. The combination of their states allows full Stokes polarimetry after demodulation. The wideband camera (WB in Fig. 2.2), placed before these two components, provides a valuable reference and anchor channel as will be shown later. At the end of the beam there are two cameras. These see complementary polarization states from being placed after a 50/50 polarizing beam splitter which enables reduction of the seeing-induced cross-talk between measured states when the images from the two cameras are combined.
Figure 2.3: Blue Tower in action. To the left on an elevated plane the PD and WB cameras are seen. At the furthest left in the image the fixed wing filter camera is visible. The blue reflection furthest away from the viewer is from the tiltable filter, mounted on a rotation stage. Photo by Dan Kiselman.

2.5 Image reconstruction and MOMFBD

Seeing varies with time much faster than the solar atmosphere does, with time-scales in the order of milliseconds. This is both a curse and a blessing. A curse since data with different seeing characteristics will be harder to interpret together. A blessing because we can use the Sun as a fixed reference to take many realizations of this seeing and correct for it. This is the principle behind image reconstruction. The method of Multi-Frame Blind Deconvolution (Löfdahl, 2002) uses these different realizations by assuming the following model:

\[ D_{ij} = F_i \cdot S_{ij} + N_{ij}, \]  

where \( D_{ij} \) is the Fourier transform of our observed image at the instant \( j \), \( F_i \) is the Fourier transform of what would be a perfect image of Sun, \( S_{ij} \) is the Fourier transform of the seeing point spread function (PSF) and \( N_{ij} \) the Fourier transform of a noise model (for example Gaussian). Spatial frequency coordinates are omitted for simplicity. Different time periods (\( j \) index) will give
different samplings of $S_{ij}$ via $D_{ij}$. With a non-linear model fitting approach, $S_{ij}$ can be determined and PSF’s that compensate for them computed and applied in a deconvolution step that allows us to obtain the true $F_i$.

The index $i$ stands for object number (where different values of $i$ can represent different wavelengths, and/or polarization states), taking advantage that the Sun looks different at different wavelengths thus constraining $S_{ij}$ better. This was proposed in [Löfdahl (2002)] and led to a C++ implementation by [van Noort et al. (2005)] known as Multi-Object Multi-Frame Blind-Deconvolution (MOMFBD). The different objects can be given different weights depending on characteristics like noise (used for the method described in Chapter 3). This program is the core of all SST image-data reduction. The different cameras are aligned to sub-pixel precision in software using images of a pinhole array at the telescope’s primary focus. Phase diversity (PD), defocused images are also used for better constraints.

A further complication that image restoration has to deal with is that different lines of sight will pass through different layers of atmospheric turbulence thus leading to spatial variations of blurring and image position shifts, the latter leading to geometrical distortions (“warping”). MOMFBD deals with this anisoplanatim by calculating the compensation PSF’s for different sub-fields along the field of view and then shifting these subfields and mosaicking them together for a final image. The size of the sub-fields introduces a limitation discussed and compensated for in Chapter 3.

For more information on solar image restoration we refer the reader to [Löfdahl et al. (2007)].

2.6 Reduction pipelines

Here the data reduction steps used for both the blue tower and CRISP are summarized in a list form. Most steps were scripted in IDL. The non-linearity correction for one of the blue cameras was introduced in MOMFBD (C++).

Blue tower data reduction (see Paper I and Paper II for details):

- Non-linearity CCD gain correction
- Camera alignment with images of deconvolved pinholes
- Dark correction and flat fielding
- MOMFBD with “extra image objects” (Chapter 3)

1 With a server/client setup ideal for cluster usage and workstation farming.
- Compensation for tilted-filter PSF effects
- Dewarping using extra image objects
- Noise filtering

The CRISP data reduction followed different steps for the C i 538.0 nm and Fe i lines due to the different strengths and polarimetric characteristics of these two data sets. Also the seeing was remarkably stable for the C i line and thus the dewarp method (at the time in its early stages) led to negligible improvements. More attention was given to the polarimetry of the Fe i lines in order to obtain clean Stokes Q and U.

**CRISP reduction for C i 538.0 nm as used in Paper IV (see SOM of Paper IV for more details):**

- Camera alignment with pinhole images
- Dark correction
- Flat fielding with wavelength-dependent flats
- MOMFBD reconstruction
- Removal of a continuum flat similarly to what was done by Scharmer et al. (2008a)
- Demodulation following Scharmer et al. (2008a)
- Cavity error compensation and wavelength calibration
- Straylight compensation

**CRISP reduction for the Fe i lines at 630.15 nm and 630.2 nm (as used in Paper III and Paper V):**

- Camera alignment with pinholes
- Dark correction
- Flat fielding with one wavelength independent flat per camera: a de-modulated Stokes I flat in the continuum between both lines at the same point used for polarization calibration
- MOMFBD with extra image objects
• Noise filtering
• Dewarping using extra image objects
• Demodulation for the instrumentation polarization
• Combine CRISP T and CRISP R cameras
• Demodulation for the telescope’s polarization using the model from Selbing (2010)
• Cavity error compensation and wavelength calibration
• Straylight compensation

In the blue pipeline the noise filtering removes high-frequency noise enhanced by the compensation scheme described in Paper I. In the CRISP pipeline it removes very high frequency fringes in the corners of the field of view that appear from using a single flat per camera for the Fe I lines data. Using a single continuum flat prevents some complications due to the quiet-sun line-profile being present in the flats and saves the flat removal step used for 5380. However, wavelength-dependent fringes are present and are enhanced by image reconstruction. Fortunately, for this data set, these had very high frequencies thus being easily filtered without loss of spatial resolution. Otherwise wavelength-dependent flats processed like Schnerr et al. (2011), could also be used to solve these fringes for the Fe I lines.

The main improvements for future image reduction coming from these pipelines are the compensation scheme for a tiltable filter as described in Paper I and the extra dewarping step described in Chapter 3.

2.7 Introducing Dewarping

In solar physics, “dewarping” or “destretching” frames to one another is a commonly used technique, for example, when producing time-series (like the movie produced for the sunspot used in this paper (Henriques, 2011)). It is a procedure that can be roughly summarized in the following way: a small sub-field of one image is taken and shifted across a second image while computing a cross-correlation matrix at each point. This provides a map of how well that sub-field matches each portion of the second image. Then the displacements necessary to obtain the best match for every single subfield can be used to shift the subfields of the first image into a corrected third image. Naturally this process involves interpolating intensities between pixels, smoothing of the matrix of the measured displacements (preferably with overlap of sub-fields),
outlier removal, and often requires iterative correction, derotation, full image alignment, and intensity normalization or other pre-processing steps. These, however, are well understood and fairly standard when reducing solar data and thus provide no complications. This fundamental procedure is frequently used in solar physics and is central to one of the techniques developed in Paper II (technique discussed in detail in Chapter 3). For computing the displacement vectors and obtaining satisfactory outlier removal, sub-routines from Dr. Peter Sütterlin (private communication) and from [Shine et al. (1994)](adapted to IDL by Dr. Tom Berger) were implemented in the reduction pipelines.
3. Improvements in image reconstruction

3.1 The Problem

Image reconstruction with MOMFBD, while very powerful, is unable to compensate for some small-scale effects. Even if the seeing is excellent, high-altitude turbulence often causes geometric distortions varying at small angular scales. These distortions vary quickly with time, within the time-frame of a full scan reconstruction and thus must be corrected for. MOMFBD corrects for blurring effects that do not vary strongly over the sub-field and for distortions that vary at a scale larger than the sub-field size. However, high-altitude seeing distortions often vary over scales smaller than the size of a MOMFBD sub-field. Due to this, even for small shifts, very different structures can be sampled in the same pixel position at different moments in time. Especially so since bright features are so often related to dark features (e.g., bright points and dark lanes). This obviously will translate to false seeing-induced signals when differentiating data and also impact quantities computed from line profiles such as Doppler signals and Stokes vectors leading to erroneous or noisy velocities and magnetic field properties.

Attempts to compensate for this have been, so far, hardware based (where the ultimate hardware solution is to place your telescope on a spacecraft), and limited to tuning in light polarization and not wavelength. In some polarimeters (for example, the Zurich Imaging Polarimeter (ZIMPOL [Stenflo et al., 1992])) the hardware is designed to provide very fast modulation of the polarization states limiting the seeing changes between exposures and allowing interleaving of the acquisitions of the different measurements thus averaging seeing changes. This works very well when modulating only the polarization signal since you only need four states to obtain full Stokes vectors but it is quite a different matter with an imaging instruments (such as CRISP) tuning also in wavelength.

This problem was addressed in Paper II using software, in the context of the MOMFBD reconstruction scheme. It was used also for Paper III and Paper V as well as in other publications (Scharmer et al., 2012; Sekse et al., 2012a,b; Watanabe et al., 2012). The procedure is now becoming standard in
SST data processing pipelines.

In this chapter we present the method complementing the information presented in Paper II, including implementation, and provide some extra background.

3.2 The Method

In order to compensate for the geometrical distortions mentioned in the previous section, dewarping (explained in Section 2.7) is used. A displacement vector matrix is necessary to shift and re-sample the pixels into a corrected image. Narrowband images from different pass-bands, and/or polarization states, are not usable since they show different structures and thus cross-correlation would fail. However, in all imaging setups at the SST, there is always at least one wideband camera (WB) acquiring images at a fixed wavelength (and fixed polarization state), which is synchronized and aligned with the narrowband cameras. If we use only the WB frames recorded simultaneously with the frames of our narrowband (NB) and introduce them as an extra object in MOMFBD, then we will obtain one reconstructed WB image that was affected by exactly the same seeing distortions and went through exactly the same image reconstruction process as our NB camera. This reconstructed extra WB object can thus be compared with a selected reference WB image to compute a displacement matrix and apply it to the NB objects using dewarping as explained in Section 2.7. The most natural reference WB image with which to compute these displacements is the all-frames reconstructed WB (the end result of “WB anchor” in Fig. 3.1).

This procedure does not necessarily truly correct for seeing as it will merely be forcing the distortions in the NB object to be same as in the WB anchor channel. However, the most important aspect of this processing is precisely that the different NB channel reconstructions all have the same distortions, leading to perfect alignment of the different quantities or layers measure at the different NB objects.

So the procedure in the context of MOMFBD reconstruction is the following:

1. Select all WB raw frames that are simultaneous with the raw frames of an NB object.

2. Input that set of frames as WB extra objects in MOMFBD (see Fig. 3.1) with zero weight (see text).
3. Take the reconstructed WB extra objects and compute a displacement matrix to the WB anchor object (right column of Fig. 3.1) using overlapping sub-fields that are smaller than the MOMFBD sub-fields.

4. Remove outliers and smooth the displacements matrix.

5. Dewarp both the “WB Extra” object and the corresponding NB object.

6. Reduce the subfield size and repeat the steps 3 to 5. The number of times to repeat this depends on the data but three iterations are usually more than adequate.

Figure 3.1: MOMFBD scheme with the extra WB objects, exemplified for two tunable filter positions. For each NB object (marked as “NB”), a collection of simultaneous WB images (marked as “WB Extra 1” and “WB Extra 2”) are selected and input as an extra object. The dark green images on top are from the WB phase-diversity camera. The scheme used for this work includes seven NB objects and their corresponding seven WB extra objects, each with 13 realizations of the atmospheric turbulence.

Using zero weight for the extra objects prevents the WB frames from being
Figure 3.2: Row 1: WB images. Row 2 left: WB image with over-plotted and exaggerated dewarp vectors from one single iteration with small cell size. Row 2 center and right: difference image between the WB extra image above and the WB reference. Each grid spacing is 0″2. The intensity scale is the same for all the images in the first row.

over-weighted when computing the correction PSF in MOMFBD. The number of iterations should be small and the final sub-field size needs to be large enough to include structures usable for cross-correlation with the reference image. In papers II and III this size was 16 by 16 pixels, or 5.5 times the diffraction limit. In Paper V the dewarping was a bit more aggressive with 9-pixels sub-field size corresponding to ~ 3 times the diffraction limit, but with more aggressive outlier removal followed by taking the median of three sub-field neighbors and a field overlap of one third of the size. In both cases the final images were carefully inspected for any artifacts from failed dewarping. Notice that, for the blue-beam data, a data-reduction step entailing the tiltable filter compensation from Paper I must occur between steps 2 and 3 (see Section 2.6).
3.3 Example in science quality seeing

In Fig. 3.2, we show an example illustrating the application of the method and its impact on a typical region with bright points and intergranular lanes. In the top row of the figure we show the reference WB and one of the WB extra objects before and after dewarping. The difference between the image before dewarp and after dewarp is visible with the help of the grid but barely. This is often the case in good seeing like the one affecting the data used in this thesis and, as mentioned above, we are discussing small scale shifts not captured by MOMFBD. However, looking at the images obtained by simply taking the difference of the before and after dewarp WB with the reference image (bottom row of Fig. 3.2), one can clearly see how tiny image shifts (mostly sub-pixel) can affect the science results. A bright-dark pattern is visible in the difference image before the dewarp matrix is applied. This is a typical pattern of misaligned images and will occur even with sub-pixel shifts when bright and dark structures are close to each other (a very common occurrence in magnetic structures in the Sun). The after-dewarp difference image illustrates to what extent the dewarping procedure removes these artifacts. Ideally the difference image would show no structure but there are some residuals. These are due to differential blurring which the method cannot improve and to the reference image generally being sharper than the extra object images due, simply, to the reference image having more raw frames available for image reconstruction. Note that the extra WB objects incidentally also provide an easy way to visualize the amount of residual differential blurring post-MOMFBD via these difference images. Judging from maps like these, the scans used in this thesis had, in general, very low differential blurring attesting the exceptional quality of the seeing.

For the example shown in Fig. 3.2, the areas where the difference images have the highest value measure \(\sim 40\%\), bright peak to dark peak, of the full wideband intensity range before dewarping. After dewarping, the worst pixels in the difference image give \(\sim 20\%\), peak to peak, of the full wideband range. For the example shown this is almost entirely due to the difference in sharpness between the reference and extra object.

In Fig. 3.3 we show the two consecutive NB channels dewarped along with two consecutive sets of WB extra channels (of which only one is shown in Fig. 3.2). Their gradient, an example of a quantity produced for science, is computed by simply differentiating the normalized intensity maps (similarly to what was done in Paper III for one of the channels). The false signal introduced by seeing before the dewarping is hardly visible in the gradient map since the true science signal dominates over the seeing artifacts. However, how much false signal the dewarp procedure is removing is visible in the difference
between gradient maps computed before and after dewarp shown in the bottom right of Fig. 3.3

**Figure 3.3:** Row 1: NB images at two different consecutive wavelengths. Row 2 Left: Gradient image computed but scaling the mean intensity of NB 2 to the mean intensity of NB 1 and taking their difference. Row 2 Right: false signal removed estimated by subtracting the gradient images produced before and after dewarping. Each grid spacing is 0′′.2.

### 3.4 A dual purpose and the importance of this technique in future telescopes

That the solar atmosphere does not evolve within the time frame of one scan is a common assumption that is already at the limit of its validity at the SST’s maximum resolution (0′′10). It is quite possible that, at these resolutions, some amount of solar evolution is already creeping in between tunings. In the example shown in Fig. 3.2, the bright points on the left move downwards while the ones on the right move upwards, suggestive of a rotation movement. Small amounts of solar evolution translating into image proper motions are indistinguishable from seeing distortions for the method as long as they occur for both the reference objects and the NB objects. If they do so, as would be the case if the motions seen in these bright points are due to solar atmosphere evolution...
(as the NB objects shown sample a height close to the height sampled by the WB), then the method would effectively “track” the structure and false signals caused by different structures coming into the same pixel at different times (for e.g., artificial temperature gradients resulting from bright points being shifted into dark-lanes), would be avoided. In this sense the method corrects for more than just small-scale seeing distortions.

For future telescopes featuring apertures larger than the SST structure evolution during a scan would become common for highly dynamic structures. Thus, the small-scale tracking character of this method would become critical.

Note that the tracking correction will only be as good as the correlation between the evolution at the layer of the NB being observed and the evolution at the reference image height. For data sets like the one obtained in the wings of Ca ii H in Paper II, the correlation between the evolution of different photospheric layers is likely very high. However, for NB imaging at the core of strong lines, for example, large-scale flows may be very different. In that case multiple reference images that sample different heights of the solar atmosphere could be used. An example using the blue tower would be to place a Ca ii K filter in the WF position shown in Fig. 2.2 thus providing tracking for the inner-wing tiltable filter positions (TF in the same figure).

1 Assuming future telescopes will successfully observe at their diffraction limit.
Improvements in image reconstruction
4. Tomography using the blue wing of Ca π H

4.1 A special line

At 398.6 nm, the Ca π H line\(^1\) is situated close to the blue limit of the observable wavelengths for optical ground telescopes thus allowing the highest possible spatial resolution for any such telescope reaching its diffraction limit. In this region of the solar spectrum the continuum is formed nearly as deep as one can see in the Sun (Ayres, 1989) and in the core of the line one can observe both the highly dynamic upper photosphere (Rutten, 1995) and the even more dynamic chromosphere to a height that is potentially even higher than well known chromospheric lines such as H\(\alpha\) according to the VAL3C atmosphere model (Vernazza et al., 1981). This is illustrated with the range of filtergrams displayed in Figures 4.2–4.5. The last of these is the line-core image which clearly suggests that we see a magnetic canopy outlined by thin fibrils connecting the surroundings of the sunspot with the pore as seen in Fig. 4.2. Mapping these chromospheric structures as filtergrams is hard since filters used so far (including the one used here) are so broad that they allow a substantial amount of photospheric light to reach the detector (Pietarila et al., 2009; Reardon et al., 2009; Rutten & Uitenbroek, 2012). Apart from some brief comments on the presence of dark fibril structures over the sunspot penumbra and umbra in Paper IV, this thesis does not cover the chromosphere. Figure 4.5 does, however, illustrate the tantalizing potential of the data.

Of interest here is instead the use of the broad line wings for determining temperature as a function of depth. There are a number of circumstances that allow this to be done directly from observations of the intensity variation in the wing. The first is that Ca π ground state is a majority species for the photospheric temperature range. The wings are completely dominated by natural damping with some contribution from collisional damping. The strong damping wings make broadening by magnetic fields, Doppler broadening from macroscopic flows and even thermal broadening negligible.

\(^1\)The Ca π H line is (of course) one of two lines in a doublet. The other line, Ca π K, can and has been used in the same way but was not observed for this thesis.
All these effects make the opacity in the line wings only weakly dependent on temperature and it is possible to derive a fairly simple expression for it.

If we now assume that the Eddington-Barbier approximation is valid and use the fact that the line wings are formed in local thermodynamic equilibrium (LTE) with negligible scattering, we can get the temperature at an optical depth of $\tau_\lambda = 1$ directly from the observed intensity:

$$T_b = B^{-1}_\lambda(I_\lambda, \lambda),$$  \hspace{1cm} (4.1)

where $I_\lambda$ is the observed specific intensity, $B^{-1}_\lambda$ is the inverse of the Planck function, and $\lambda$ the wavelength of the observations.

As will be shown in the next section, with the above it is not so difficult to convert the optical depth scales for each different wavelength points to a common physical depth scale, thus giving us a temperature tomography of the solar photosphere.

4.2 Assigning formation depths to the Ca II H wings with the Shine & Linsky method

With only a few assumptions, [Shine & Linsky 1974] obtained an expression that assigns a column mass density (with units of $g \text{ cm}^{-2}$) to each radiation
4.2 Assigning formation depths to the Ca\textsc{ii} H wings with the Shine & Linsky method

Figure 4.2: A tomographic slice: photosphere between the sunspot and a region with pores as seen through the 1 nm wideband filter placed in the near continuum between the Ca\textsc{ii} K and the Ca\textsc{ii} H lines. The tickmark spacing is 1″.

temperature measured at each wavelength sampled in the Ca\textsc{ii} K line wings. Their expression was re-derived by Rouppe van der Voort (2002), with all the coefficients clarified, making it easier to adapt the analysis to similar lines such as Ca\textsc{ii} H (as was done in Paper II). In this section we expand a bit the derivation of these expressions from what is shown elsewhere, in order to provide insight and to clarify some details.

For a bound-bound transition the monochromatic cross section, neglecting stimulated emission, can be written using the Lorentz profiles produced by the radiative and collisional (van der Waals) broadenings ($\gamma_{\text{rad}}$ and $\gamma_{\text{vdW}}$ respectively), convolved with the Gaussian profile produced by thermal broadening,
thus generating a Voigt profile:

\[
\sigma_\lambda = \frac{\sqrt{\pi} e^2}{m_e} \frac{\lambda_0^2 f_{\text{lu}}}{c^2 \Delta \lambda_D} H(a, \lambda), \tag{4.2}
\]

where \(m_e\) is the electron mass, \(c\) the speed of light, \(e\) the electron charge, \(f_{\text{lu}}\) the oscillator strength, \(\Delta \lambda_D = \frac{\lambda_0}{c} \sqrt{\frac{2k_bT}{m_a}}\) the Doppler width (where \(m_a\) is the mass of the atom and \(k_b\) the Boltzmann constant). \(H(a, \nu)\) is the Voigt function with:

\[
\nu = \frac{\Delta \lambda}{\Delta \lambda_D}
\]

\[
a = \frac{\lambda^2}{4\pi c} \frac{[\gamma_{\text{rad}} + \gamma_{\text{vdW}}]}{\Delta \lambda_D}, \tag{4.3}
\]
4.2 Assigning formation depths to the Ca\textsc{ii} H wings with the Shine \& Linsky method

Figure 4.4: A tomographic slice: upper photosphere for the same field as Fig. 4.2 as sampled by the tiltable filter in the Ca\textsc{ii} H inner wing. The tickmark spacing is 1′′.

where $\Delta \lambda = (\lambda - \lambda_0)$ is the wavelength distance from the line center. The Voigt function can be approximated by the sum of the Lorentz and Gaussian components:

$$H(a,\nu) \sim e^{-\nu^2} + \frac{a}{\sqrt{\pi} \nu^2}.$$  \hspace{1cm} (4.4)

The method uses the wide damping wings of Ca\textsc{ii} H and K far from the Doppler core. Thus the first term in Eq. 4.4 above can be dropped and from Equations 4.2, 4.3, and 4.4 we get:

$$\sigma_\lambda = \frac{e^2 f_{\text{Cu}} A_0^4}{mc^2} \frac{1}{\Delta \lambda^2} \left[ \gamma_{\text{rad}} + \gamma_{\text{vdW}} \right].$$  \hspace{1cm} (4.5)

This expression is adapted to Ca\textsc{ii} H by using the appropriate values (see Pa-
Figure 4.5: A tomographic slice: same field as Fig. 4.2 as sampled by the tiltable filter at the line-core of Ca\textsc{ii} H, showing the chromospheric canopy connecting the sunspot to the pore region (opposite polarity magnetic features). The tickmark spacing is 1".

per II) for the radiative damping constant ($\gamma_{\text{rad}}$), the oscillator strength $f_{\text{lu}}$. In order to combine it with the constraint of hydrostatic equilibrium, and for clarity in this derivation, we want to write it as an expression for the mass extinction coefficient. We use the relation $\kappa = \sigma n_l$ where $n_l$ is the number density of absorbers. In our case the absorbers are Ca\textsc{ii} ions in the ground state. Since nearly all calcium ions are in the ground state for the photospheric temperature range in which the wings are formed, our density of absorbers is directly proportional to the number density of hydrogen atoms ($N_\text{H}$) via the
4.2 Assigning formation depths to the Ca\textsc{ii} H wings with the Shine & Linsky method

solar calcium abundance ($A_{\text{Ca}}$): $n_l = \sigma A_{\text{Ca}} N_\text{H}$. Thus:

$$\kappa_{\Delta \lambda} \rho = \sigma A_{\text{Ca}} N_\text{H} \frac{e^2 f_{\text{lw}} A_{\text{Ca}}^4}{m_e 4\pi c^3} \frac{1}{\Delta \lambda^2} \left[ \gamma_{\text{rad}} + \gamma_{\text{vdW}} \right] N_\text{H}. \quad (4.6)$$

The van der Waals broadening term ($\gamma_{\text{vdW}}$), which essentially measures how much the energy of the absorbed or emitted photons is changed by interactions with (mostly) neutral hydrogen atoms, is temperature dependent (since the more the particles move the more collisions you have). This dependency complicates the analysis somewhat by introducing another dependence of temperature and $N_\text{H}$. The van der Waals broadening term can be written as:

$$\gamma_{\text{vdW}} = \Gamma_W \left( \frac{T}{5000 \text{K}} \right)^{0.39} N_\text{H}, \quad (4.7)$$

where $\Gamma_W$ was calculated by Rouppe van der Voort (2002) using the collisional cross-sections from Barklem & O’Mara (1998).

To proceed, we assume that the gas is in hydrostatic equilibrium, that is, that the atmosphere is stationary with gas pressure gradients and gravity at balance (thus neglecting magnetic forces that most probably are present). This gives us a height dependence:

$$\frac{dP_{\text{gas}}(z)}{dz} = -g \rho(z), \quad (4.8)$$

where $P_{\text{gas}}$ is the gas pressure, $z$ is height, $g$ is the solar surface gravity and $\rho(z)$ is density. A geometrical height can be converted to optical depth ($\tau$) using the mass extinction coefficient $\kappa_{\lambda}$:

$$d\tau_{\lambda} = -\kappa_{\lambda} \rho dz. \quad (4.9)$$

We can then integrate Eq. 4.8 to obtain the pressure at a given radial optical depth (the optical depth as measured along the perpendicular to the surface). Since our goal is to couple our observed intensity with the local thermodynamical conditions, and since our radiation samples the conditions at $\tau = \mu$ (Eddington-Barbier approximation where $\mu$ is the cosine of the angle between the line of sight and the vertical to the surface), this is the height we integrate to:

$$P_{\text{gas}}(\tau_{\lambda} = \mu) = \int_{z(\tau=0)}^{z(\tau=\mu)} g \rho dz = \int_{\tau=0}^{\tau=\mu} \frac{g}{\kappa_{\lambda}} d\tau_{\lambda}. \quad (4.10)$$

So now we have coupled a thermodynamical quantity, pressure, with an optical property: extinction. For a completely forward method this integral must be approximated by a one point quadrature:

$$P_{\text{gas}} = q \mu g / \kappa_{\lambda}, \quad (4.11)$$
where the weight $q_1$ was chosen by [Rouppe van der Voort (2002)] after tests in a range of model atmospheres. This quadrature and the ideal gas law in the form $P = \frac{\rho}{\mu_{\text{mom}} m_u} k_b T$ give us the extinction coefficient as a function of temperature:

$$
\kappa_\lambda \rho = \frac{\mu_{\text{mom}} m_u q_1 \mu g}{k_b T},
$$

(4.12)

where $\mu_{\text{mom}}$ is the mean molecular weight, $m_u$ the atomic mass constant. Notice that $\kappa_\lambda$ is the total extinction, both from Ca \textsc{ii} H (here: $\kappa_{\Delta \lambda}$) and from the continuum. Assuming the Milne-Eddington approximation, the ratio between these two extinctions is constant with height. Thus the ratio of the integral of both extinctions (the ratio of both optical depths) will also remain constant throughout the atmosphere and one can compute the fraction of how much of the total radial optical depth ($\tau = \mu$) actually comes from Ca \textsc{ii} H by simply subtracting the continuum optical depth ($\tau_{\text{cont}}$). With that fraction we can obtain the line extinction coefficient from Eq. 4.12:

$$
\kappa_{\Delta \lambda} \rho = \frac{\mu_{\text{mom}} m_u q_1 \mu g (\mu - \tau_{\text{cont}})}{k_b T},
$$

(4.13)

which can also be written as:

$$
\kappa_{\Delta \lambda} \rho = \frac{\mu_{\text{mom}} m_u q_1 \mu g}{k_b T} (1 - \tau_c),
$$

(4.14)

where $\tau_c$ is the fraction of the total opacity due to continuum as it was computed for the appropriate $\tau$ value in the reference atmosphere in [Paper II][1] and named to follow the nomenclature of the previous literature on this method.

Now we have two expressions for $\kappa_{\Delta \lambda}$ (Eq. 4.14 from hydrostatic equilibrium and Eq. 4.6 from atomic and collision physics, both assuming we are sampling $\tau = \mu$) and can combine them to eliminate the extinction and $\rho$ dependencies and obtain a quadratic expression for $N_H$ that depends solely on wavelength, temperature, known physical parameters, and radiation broadening (temperature independent):

$$
\frac{\mu_{\text{mom}} m_u q_1 \mu g}{k_b T} (1 - \tau_c) = \frac{e^2 f_{\text{lu}} A_{\text{Ca}} q_1^4}{m_e 4 \pi c^3} \frac{1}{\Delta \lambda^2} \gamma_{\text{rad}} N_H + \frac{\Gamma_W}{\Gamma_{W}} \left( \frac{T}{5000 \text{K}} \right)^{0.39} N_H^2.
$$

(4.15)

Solving for $N_H$ leads to the central expression of the method:

$$
N_H (\Delta \lambda) = \frac{1}{2} \left( \frac{5000 \text{K}}{T} \right)^{0.39} \left[ \frac{\gamma_{\text{rad}}}{\Gamma_W} + \left( \frac{\gamma_{\text{rad}}}{\Gamma_W} \right)^2 + \right]^{1/2}
$$

$$
\frac{4 g \mu_{\text{mol}} m_H}{A_{\text{Ca}} \Gamma_W k_b} \frac{m_e 4 \pi c^3 q_1}{e^2 f_{\text{lu}} A_{\text{Ca}} q_1^4} \left( \frac{T}{5000 \text{K}} \right)^{0.39} \frac{\Delta \lambda^2}{T} (1 - \tau_c) \right]^{1/2}
$$

(4.16)

Where the opacity from other, blending, lines as seen in Fig. 4.1 was also included.
Finally, column mass density is \( m = \int g \rho dz \). From Eq. 4.10 this is \( P/g = m \) which, again using the ideal gas law with \( \frac{\rho}{\mu_{\text{mom}} m_a} = 1.1N_{\text{H}} \) and gives us our unit of depth:

\[
m = 1.1N_{\text{H}}k_bT_b g^{-1}.
\] (4.17)

The factor 1.1 comes from there being 10 hydrogen atoms for every helium atom and disregarding other elements. So now one can assign a depth in units of column mass density to the observed radiation temperatures in an easy-to-implement forward fashion.

The method described above was originally developed by Shine & Linsky (1974) with high-resolution spectra in mind, and applied on such by Rouppe van der Voort (2002). In Paper II it was generalized for use with filtergrams acquired with the tiltable-filter setup described in Sect. 2.3. These filtergrams have \( 4 \times 10^6 \) pixels, which makes such a fast analysis tool attractive, especially while the new imaging processing techniques of Papers I and II were being developed and tested. The method was then used again in Paper III to produce temperature gradient maps for the sunspot’s penumbra.

4.3 Testing

For the tests of Paper II we used field-free hydrodynamic (HD), and magnetohydrodynamic (MHD) simulated atmospheres, for which synthetic spectra were computed and then analyzed. The MHD atmosphere presented calibration issues due to its strongly reduced temperature relative to the reference atmosphere needed for intensity calibration and for setting some of the physical parameters above. Therefore in Paper II we focused on the HD atmosphere. However, the tests with a MHD simulation gave interesting results as well. While the test showed errors that were overall larger then in the HD test and the outcome is somewhat difficult interpret due to the intensity calibration issues, it actually performs quite well in the temperature extremes of the atmosphere. This is interesting because magnetic forces are ignored in the derivation above, while the magnetic field is very strong in the simulation columns corresponding to these temperature extremes. To illustrate this, one of the scatter plots with extracted temperature versus the known temperature from the test MHD atmosphere is reproduced in Fig. 4.6. There the extremes of the temperature plot, corresponding to pores and bright points, do not show large errors.
Figure 4.6: Scatter plot of the processed pixels for the MHD simulation in Paper II. The vertical axis shows the true temperature in the simulation while the horizontal axis is the temperature recovered from synthetic spectra. The straight line represents a perfect result.
5. Summary of Papers

5.1 Overview

All the papers in this thesis use data from the 23 May 2010. Most of them come from the same ~ 30 s span of science data, selected for their quality from nearly a full day of observations, with only Paper I using its calibration and test data from other observing occasions. To place some perspective into this, the data from these 30 s measure ~ 4 gigabytes and required ~ 385 gigabytes of calibration data to get it right.

The following summary is organized like the data: blue stands for Ca ii H data and red for CRISP data.

5.2 Blue-beam Papers

Tilting an interference filter is a very useful technique to change the transmission profile of an interference filter by extending the effective size of its cavities (Beckers, 1998). It is frequently used to fine-tune broad-band filters such as the prefilter in front of CRISP (see Fig. 2.2). This process can be taken a step further. One can use larger tilts and change the tilt angle every few exposures, thus providing a simple tunable device that can effectively scan different wavelengths in a small range. This technique is used in all the papers involving blue-beam data to scan the blue wing of the Ca ii H line.

However, whereas for very small tilts and for fixed filter positions, one can ignore subtle effects on the point-spread function (PSF), the same is not the case when acquiring data at large tilt angles. This leads to somewhat unexpected challenges due to the interlocked nature of the image-reconstruction procedures used, the requirement that the non-simultaneous data be perfectly aligned, and a number of tilt-angle dependent effects on the filter PSF and pass-band. The latter include PSFs with different degrees of asymmetry, spatially shifted PSFs, and different pass-bands in wavelength.

In Paper I these challenges are addressed by modeling the filter effects from the variable apodization of the pupil when the filter is tilted. A compensation scheme for the PSF effects is devised. Two observational tests are performed. A measurement of the filter profiles, using the TRIPPEL spectro-
graph at the SST (Kiselman et al., 2011), shows that the filter profiles have the expected central wavelength but are slightly narrower in passband and have a slightly lower peak transmission than reported by the manufacturer. In the second test the compensation method is applied to data from Paper II.

In Paper II the scheme from Paper I is re-applied to the data from 23 May 2010 including reprocessing of the alignment calibration data (pinholes) so that the data from all the different wavelengths are perfectly aligned at the end of the reduction procedure. This was very important as one of the main goals of Paper II is to produce temperature gradient maps, which will suffer from errors from any non-solar differences between the observed images at different wavelengths. The noise filters from the compensation scheme provided adequate degrading filters that were used to degrade synthetic observations computed from MHD and HD simulations in order to be compared to the observations (described in more detail in Chapter 4).

Still in Paper II a method was developed to address the issue of high-altitude seeing which produces small-scale misalignments between non-simultaneous frames. It is based on dewarping using additional alignment wideband channels in the reconstruction procedure (described in detail in Chapter 3). The quality of the final temperature-gradient maps attests to the success of accounting for all the different alignment challenges. This last method proved useful for other types of data and is becoming standard in the SST data reduction pipelines and was used by Sekse et al. (2012a,b); Watanabe et al. (2012), and Scharmer et al. (2012).

Also in Paper II, active-region observations are compared with MHD synthetic observations and quiet-sun observations are compared with HD synthetic observations. The comparison is done using maps of intensity as well as maps of vertical temperature gradient from different depths. An interesting pattern, variable with height, is identified in the gradient maps for both synthetics and observations. This consists of a near perfect inverse relation between the presence of low gradient levels and strong magnetic field structures that is independent of light intensity and that varies with height in nearly the same way in both observations and synthetics.

Paper II makes use of an analytical inversion technique, originally developed by Shine & Linsky (1974), to extract temperature as a function of depth. The technique is tested for the first time in filtergrams and at ~0′′10 resolution. This technique is discussed in detail in Chapter 2. It also tests the spectral limitations of the filter profiles.

The techniques and tests in Paper II open the door to the usage of tunable filters with much narrower passbands in the blue end of the spectrum and allow for strongly reduced seeing-induced noise in non-simultaneous observations such as the ones in Paper V.
5.3 Red-beam Papers

In Paper IV the \( \text{C}_i \) 5380 Å line is analyzed. Seeing was so outstanding that the dewarp method led to negligible improvements (where the advantage of longer wavelength over \( \text{Ca II H} \) might also have played a role when comparing seeing effects).

The line has a high excitation potential (7.9 eV) and is formed at high temperatures. This is both an advantage and a disadvantage. The high temperatures mean that the line will be formed deep. Thus measuring Doppler signal from this line provides access to deep flow patterns. This is important as the flows we observe are most likely the “overshooting” part of a convective flow pattern driven from below the visible surface, and we want to observe as close to the “source” of this driving flow as possible. However, the high excitation potential of the line also means that it weakens considerably in dark cool structures. Upflows are dominant even in quiet Sun granulation. Straylight will mask the presence of downflows with the brighter, stronger adjacent upflows. Observing downflows is more difficult in the penumbra where convection is weaker and the spatial scales smaller. This project required some sort of properly constrained straylight correction and good velocity calibration. Constraining the straylight was possible by using the intensity in the sunspots umbra and the granulation profiles. Velocity calibration was possible due to synthetic observations computed from HD granulation models (de la Cruz Rodríguez et al., 2011) matched to the quiet Sun observed close to the sunspot. Straylight was constrained by using the RMS of the continuum intensity, the RMS of the velocity, and the averaged velocity of the quiet sun computed from simulations and observations and making them consistent with each other (by correcting the observations or degrading the synthetics). The umbra provided an important limit on the extent of the wings of the straylight as this cannot be negative and is already only 15.6% of the average quiet sun in the uncompensated data.

However the exact straylight PSF remains unknown and the existence of convective downflows throughout the penumbra was not predicted by most penumbra models. Thus robust results were sought. One of the paths to this was to show that the exact shape of the straylight PSF is actually not important. The other path was provided by the sunspot itself, as red shifts were observed also in the disk center side, even as the stronger Evershed flow will create a dominance of blue shifted profiles there. This is because the sunspot was observed at a heliocentric distance of 15°. To separate horizontal and vertical flows, a fit was made assuming that the flow patterns, on average, do not vary with azimuth. Making such a fit using only pixels that are locally dark (cold) lead to a downflow of 0.6 km/s and an Evershed flow of 3.5 km/s. Locally
bright pixels showed a radial outflow of 3.2 km/s and upflows of 1.8 km/s. The relation between intensity and vertical flow velocity was shown to follow a similar (though slightly weaker) relation as the one seen for granulation in the quiet sun, a clear convective signature.

The spatial relation between the flow pattern and vertical magnetic field was possible by using the total circular polarization (TCP) from the \( \text{C} \text{I} 538.0 \text{nm} \) line (the line is weakly magnetically sensitive with a Landé \( g \) factor of 1) and estimation of inclinations with the same fitting procedure. While both spines (corresponding to the penumbral component with a strong vertical magnetic field component) and inter-spines show the same convective signature, the inter-spines carry most of the radial outflow as expected.

Thus we claim that **Paper IV** provides the missing “clincher” in the puzzle of the different penumbral models discussed in Chapter [II].

In **Paper V** we adapted the same dewarp method as in **Paper II** to spectropolarimetric data from the \( \text{Fe} \text{I} 630.15 \text{nm} \) line and used it together with the \( \text{C} \text{I} 538.0 \text{nm} \) line. The same fitting technique as in **Paper IV** was used. Convective downflows were also observed in the wings of and with the center-of-gravity (COG) method of the \( \text{Fe} \text{I} 630.15 \text{nm} \) line although with reduced amplitude. It is again confirmed with the better magnetic field measurements, due to the much higher sensitivity of the line, that the convective signature reported in **Paper IV** is found both in spines and inter-spines while the Evershed outflows are present only in the inter-spines.

### 5.4 Combining the colors

In **Paper III**, data from the \( \text{Fe} \text{I} 630.15 \text{nm} \) and \( \text{Fe} \text{I} 630.2 \text{nm} \) lines are aligned with the \( \text{Ca} \text{II H} \) data using both the wide-band images at both wavelengths and dewarping. Total circular polarization (TCP), the integral of the module of Stokes \( V \), is computed from the demodulated \( \text{Fe} \text{I} \) data. The relation between temperature gradients and magnetic field in **Paper II** is re-examined by using TCP as a proxy for vertical magnetic field. A relation is found between TCP and low vertical temperature and intensity gradients that is valid for most of the sunspot’s penumbra. Similarly to Bellot Rubio et al. (2007), we use TCP to infer conclusions about the nature of dark cores in the penumbra of sunspots. We again see that these are more pronounced in TCP than in intensity. We also see that they are pronounced in temperature gradient, an observation that is connected to them becoming longer and more contiguous with height in the middle photosphere as observed in \( \text{Ca} \text{II H} \) wings. Furthermore, taking advantage of the high resolution and tomographic strength of the setup, small-scale structures observed in the \( \text{Ca H} \) line core over the sunspot umbra and penumbra are described. Dark fibril structures against a bright background (brightened
by an umbral flash) are visible and similarly shaped structures are observed over the penumbra in the line-core.

5.5 Looking forward

Following the line of the present work, the obvious next step would be to confront the temperature stratification results obtained in Ca ii H with temperatures derived from the red-beam CRISP data using inversion techniques (Bellot Rubio et al., 1997; Frutiger et al., 2000; Socas-Navarro et al., 1998). Such results have actually been recently produced (Scharmer et al., 2012). The outcome could be most interesting for both paths taken.

In the same like it would be valuable to incorporate Ca ii H inversions with complete LTE inversion techniques and consistent radiative transfer. This will be slower than the temperature extraction method used in this thesis but likely (much) more accurate.

A thorough analysis of the existing Ca ii H line-core data is demanded by images like the one obtained in Fig. 4.5. Compared to the study of Pietarila et al. (2009), the current data contains a sunspot and uses a narrower filter.

Finally, the Ca ii H data and analysis thereof presented in this thesis point forward to the use of even narrower filters for the study of the solar photosphere and chromosphere.
Sammanfattning

Solens yta hyser fortfarande hemligheter för vetenskapen. Solfläckarna är tex komplexa strukturer som ofta är större än vårt eget jordklot. De kan ses från jorden och deras existens har därför varit känd i hundratals år men det har inte varit lika enkelt att förstå hur de fungerar.

Denna avhandlings syfte är att hjälpa till att avslöja några av solens hemligheter. Den utvecklar metoder för att mäta temperaturen i tre dimensioner i solytans strukturer med bästa möjliga upplösning i bilder från det svenska 1-meters solteleskopet, SST, på La Palma. En teknik för att mäta småskaliga bildförvrängningar som orsakas av jordens turbulent atmosfär har utvecklats. Den är baserad på kors-korrelation, en teknik liknande den som används för att mäta rörelse i optiska datormusar. Relationen mellan temperaturens stratifiering och strukturer på solytan, som granulation, porer, små ljusa magnetiska strukturer, och en solfläcks penumbra undersöks.

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