Colloquium Talk
September 2016

Simulation of a Double/Triple-Fabry-Pérot-Spectropolarimeter for the new solar telescope DKIST

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Overview

- The new 4m solar telescope DKIST on Hawaii
  - Demanded measurement accuracy
- The imaging spectropolarimeter:
  - Visible Tunable Filter VTF
- Simulation procedure to model observations with a double/triple *Fabry-Pérot-Interferometer*
- Results for simulated observations
- Consequences for the instrument configuration

The new 4m telescope DKIST on Haleakala/Hawaii

Leader ship: **N**ational **S**olar **O**bservatory (US)

Daniel **K**. **I**nouye **S**olar **T**elescope:

Diameter D=4m

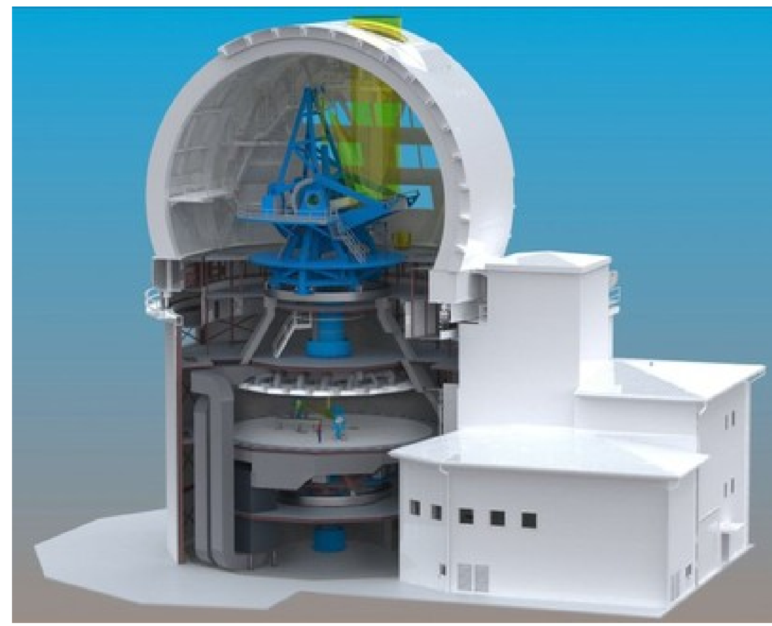
Photon flux:

~ N_{ph} = 1200 photons/ms for each resolution element in the detector plane (spectral bandwidth $\Delta\lambda$ = 6pm)

Spatial resolution:

$\alpha = \lambda / D_T$ = 0.032"@630.25nm

- ~ 20km for each resolution element in detector plane



http://www.kis.uni-freiburg.de/de/projekte/visible-tunable-filter/

Kiepenheuer-Institut für Sonnenphysik:

Development of an imaging Spectropolarimeter

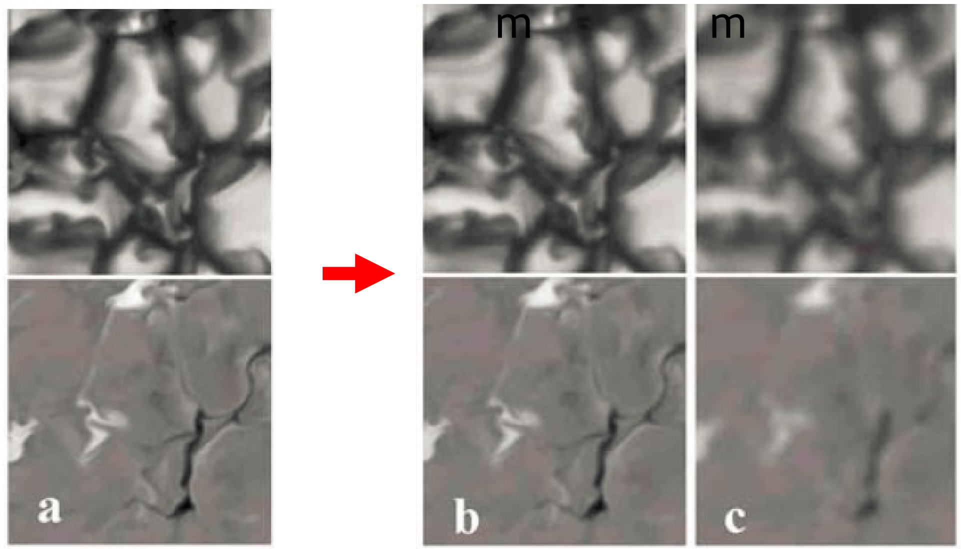
□ Study of solar absorption/emission lines and corresponding magnetic field vectors

Required accuracy for physical measurements

Simulation D_T=4 m D_T=0.75 m

Solar granulation of photosphere

-> λ_0=630.25nm, spatial resolution 11km



Intensity map

Vertical magnetic field

Decreasing resolution

Determination of line core position in the order of 0.2pm

Accuracy

Intensity resolution: ~0.2%

Doppler velocity v_D

Δv_D=100 m/s

Full width half maximum W

Magnetic field B

vertical B_{min}=20G

horizontal B_{min}=100G

'Visible Tunable Filter' (VTF)

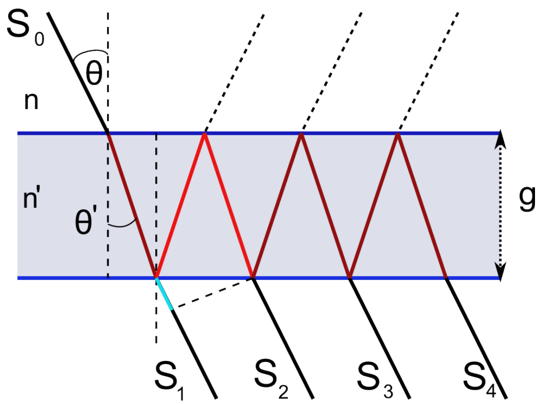
Configuration of the imaging Spectropolarimeter

- **P**re **F**ilter **PF** - FWHM $\Delta\lambda$=0.8nm
- Polarization modulator **M** □ $(I_{0,I1,I2,I3})^{T}$=**MS** with Stokes vector **S**=(I,Q,U,V)T
- Multiple **F**abry-**P**érot-**I**nterferometers **FPI**

FPI principle: two partly reflecting

coated glass plates with adjustable

air gap -> multi beam interference

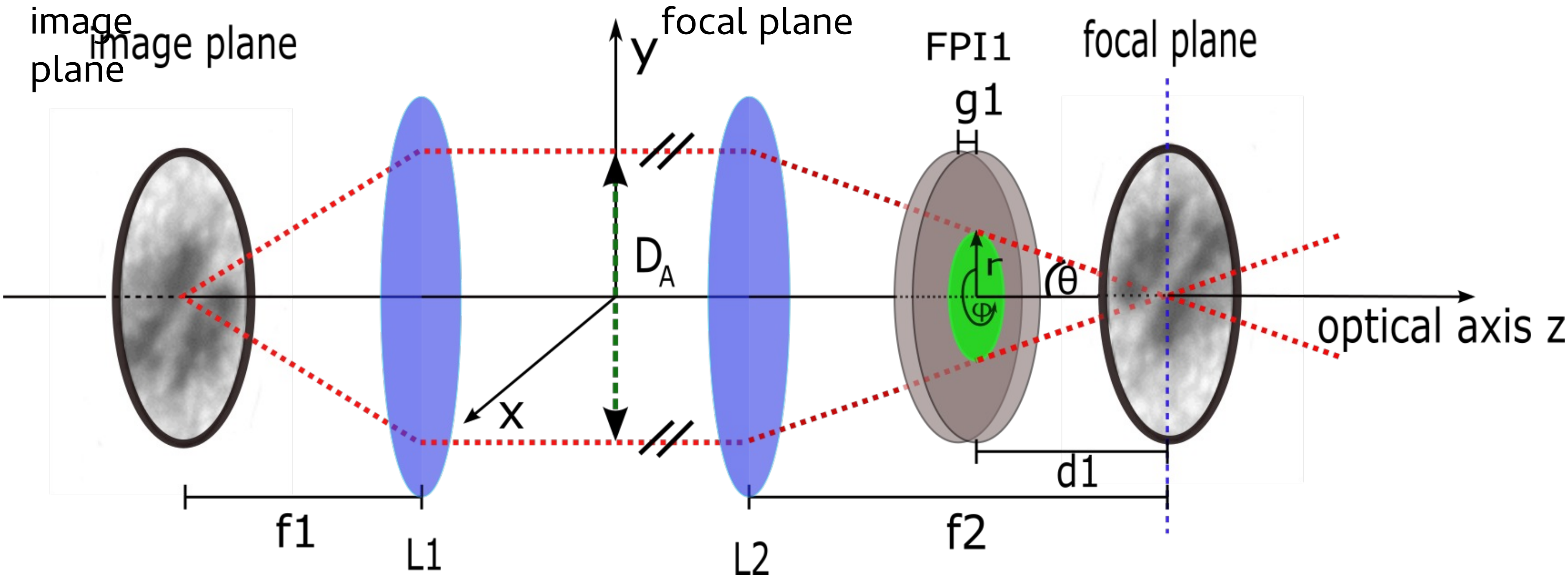


- Double/Triple system was simulated:

  Spectral **R**esolution SR=100.000/200.000 (at a central wavelength λ=500nm)
- Diameter of active area is 0.25m □ **F**ield **O**f **V**iew FOV=60''
- Telecentric mounting
- F#=200
- Range: 520-870 nm

Telecentric mounting in defocused position

Telecentric mounting of the FPIs in a 4f system

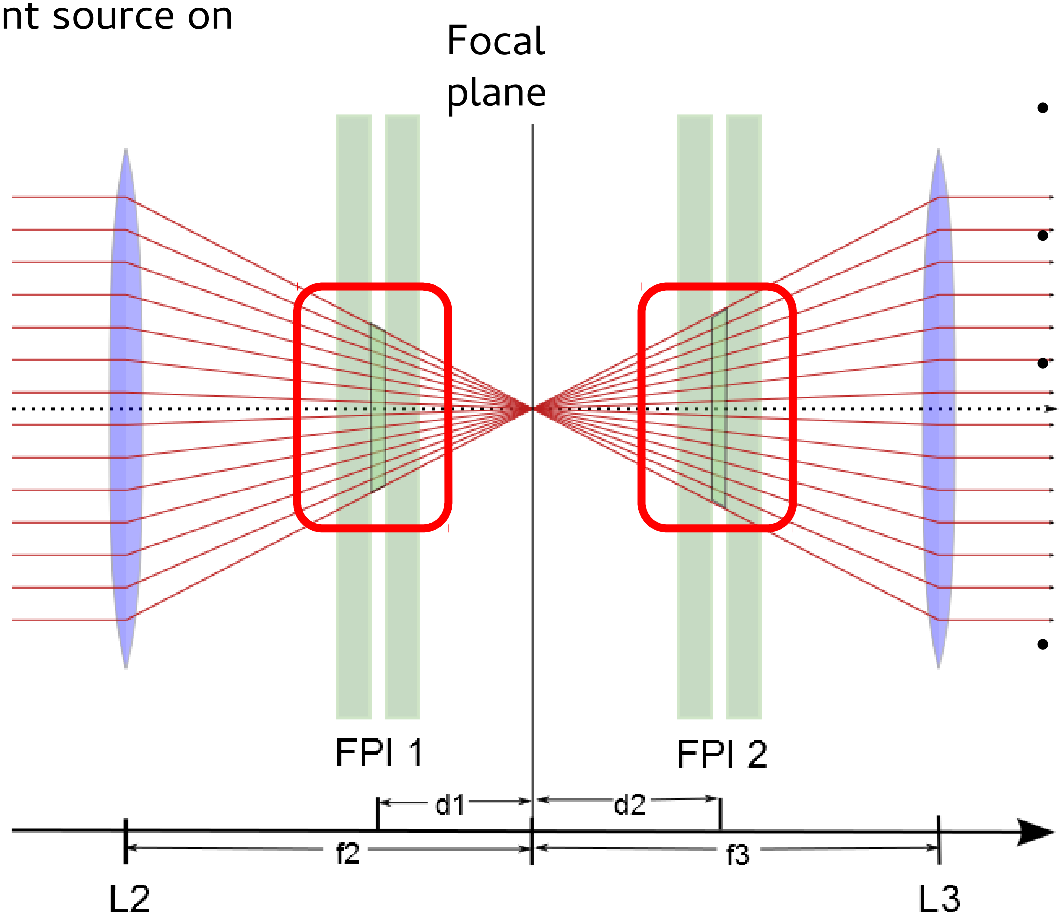


Double-FPI-system

Induced measurement errors □ variation in the line profile

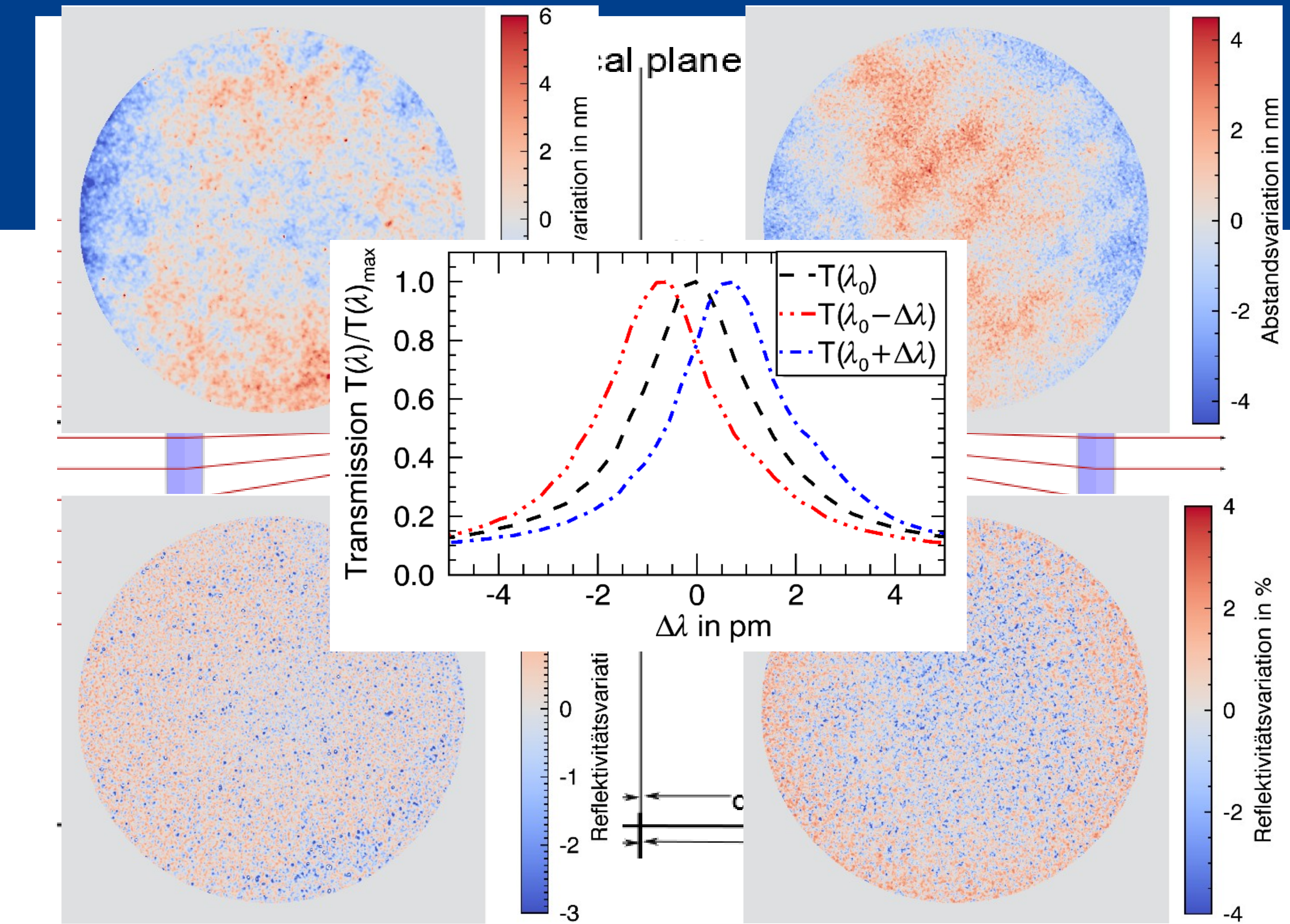
Illustration for a point source on the optical axis

- Light cone is split into individual rays
- each light ray is influenced by a different local plate error



- Gap variation shifts line profile
- Reflectivity error broadens the profile
- Individual shifts of the transmission profiles for FPI1 und FPI2 reduce the photon flux
- Asymmetry due to radial weighting within the integration over the angle spectra

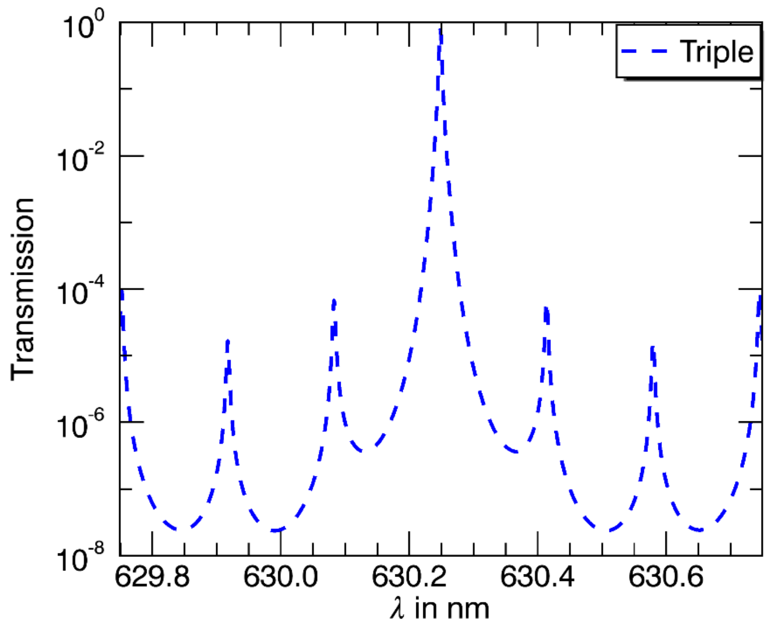
$$I_{x,y}(t) = \sum_{\lambda} I_{x,y,0}(\lambda) \prod_{i} \sum_{\theta} T^{i}_{x,y}(\lambda, \theta, R^{i}_{x,y}, \Delta R^{i}_{x,y}(\theta), g^{i}_{x,y}(t), \Delta g^{i}_{x,y}(\theta))$$

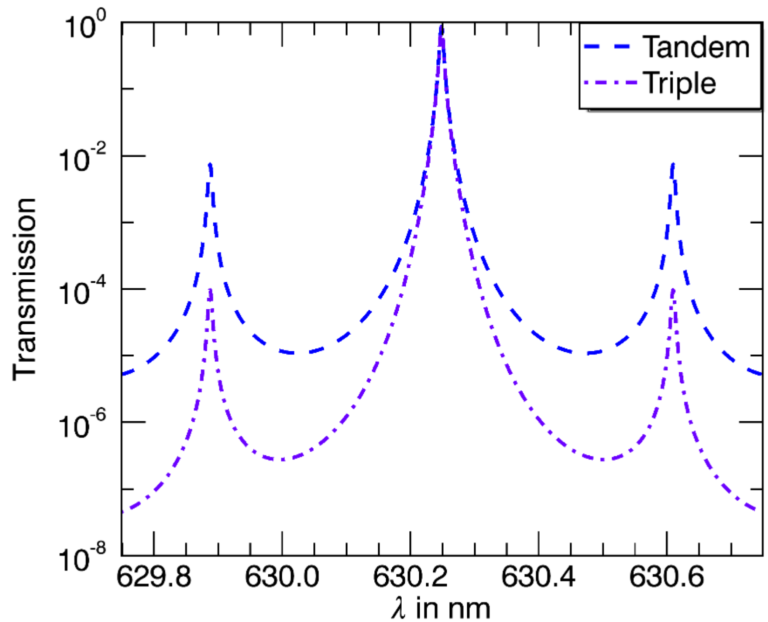

cal plane
ariation in nm
6
4
2
0
Abstandsvariation in nm
4
2
0
-2
-4
Transmission T(λ)/T(λ)max
1.0
0.8
0.6
0.4
0.2
0.0
-4
-2
0
2
4
Δλ in pm
T(λ0)
T(λ0−Δλ)
T(λ0+Δλ)
Reflektivitätsvariati
0
-1
-2
-3
Reflektivitätsvariation in %
4
2
0
-2
-4

Combining multiple FPIs

FPI-Parameter for two instrument configurations

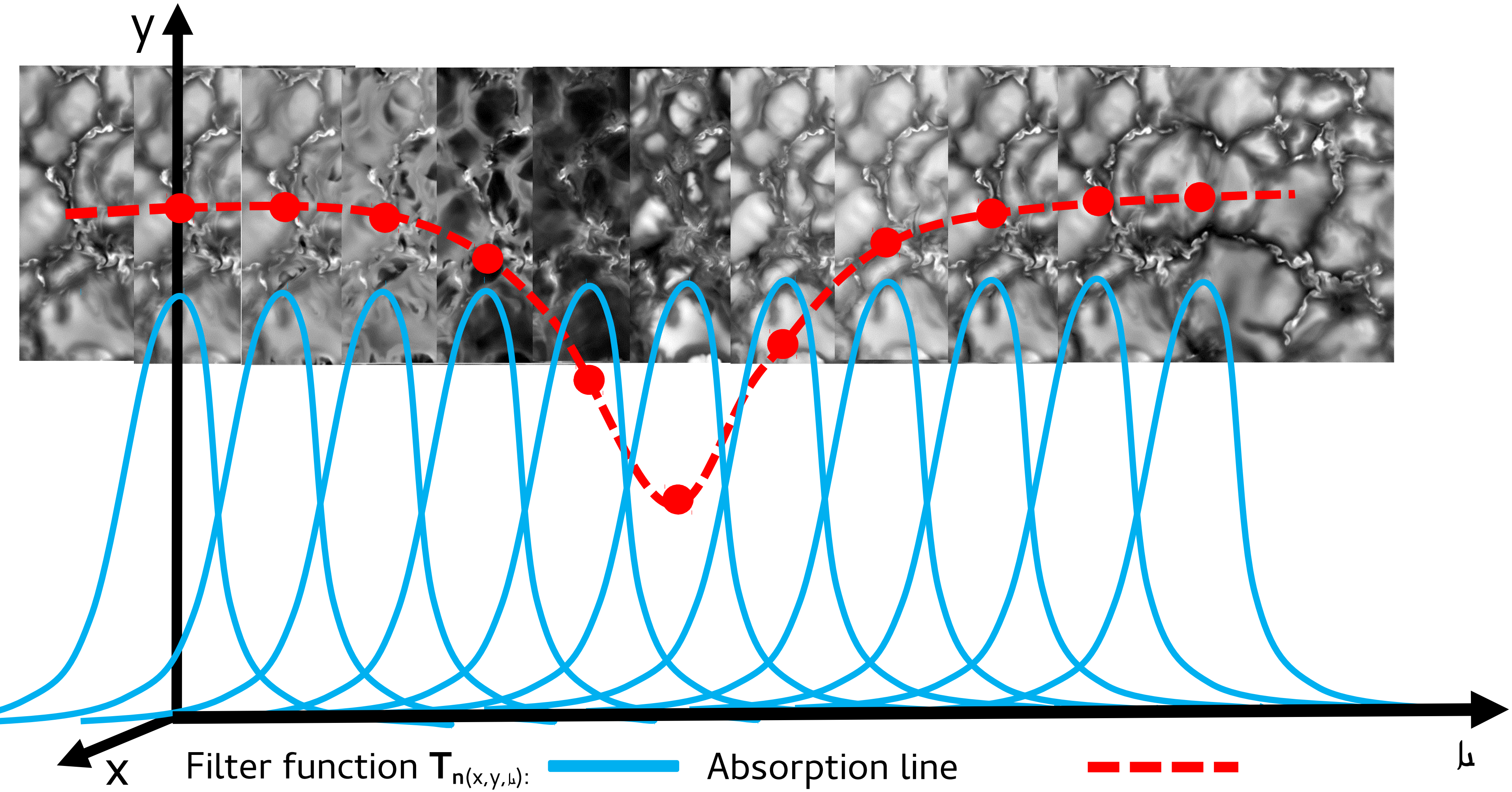
	Instrument 1			Instrument 2		
FPI	**g in mm**	**R in %**	**Finesse Fi**	**g in mm**	**R in %**	**Finesse Fi**
1	1.2	94	51	0.55	95	61
2	0.222	88	25	0.214	84	18
3	0.352	88	25	0.149	84	18





Spectroscopic line scan

Illustrated for one point in the detector plane



Filter function $\mathbf{T}_{\mathbf{n}(x,y,\lambda)}$:

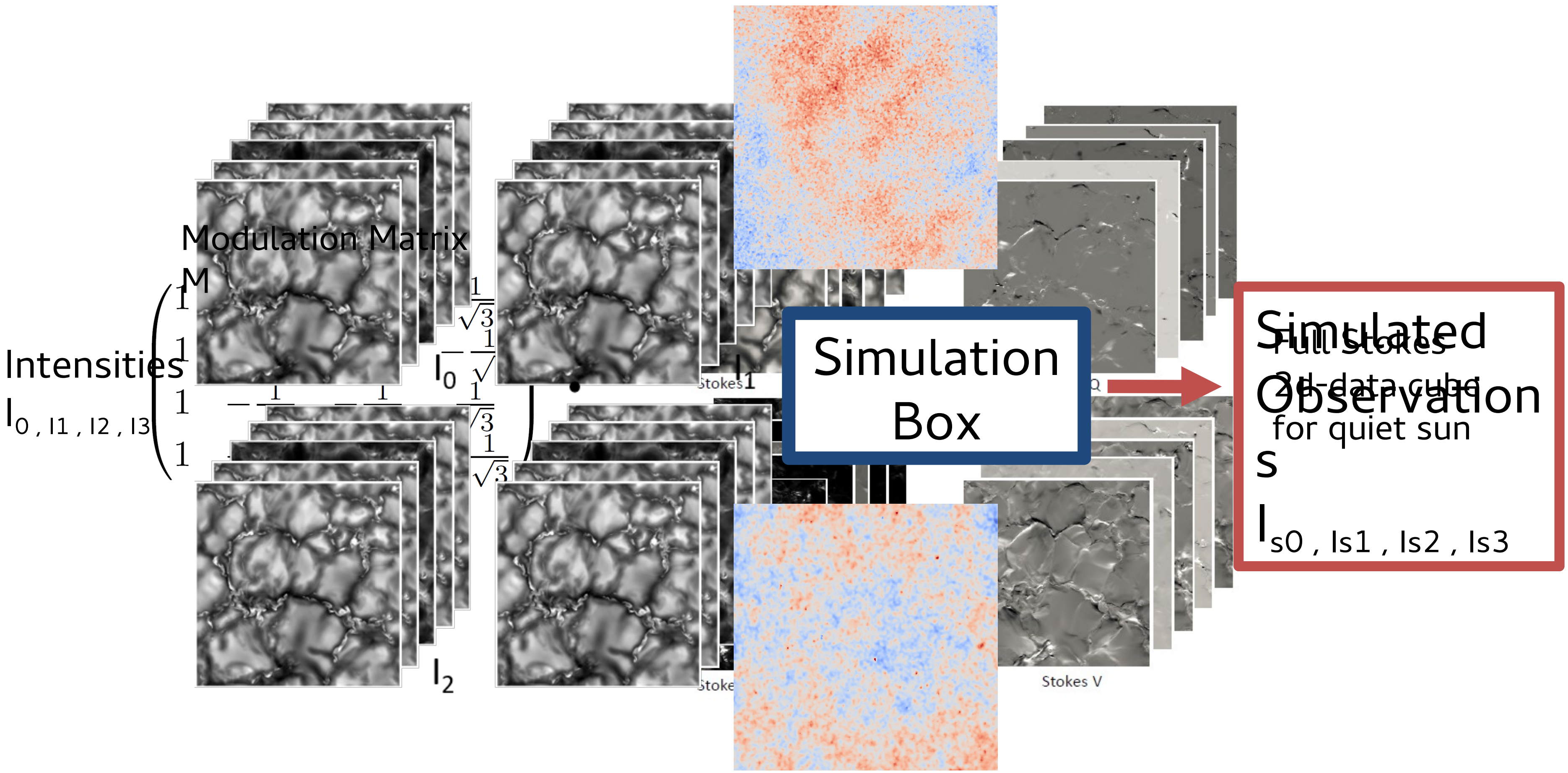
Absorption line $\mathbf{I}(x,y,\lambda)$:

observed intensity $I_n = \int I \cdot T_n \, d\lambda$:

2D simulation procedure

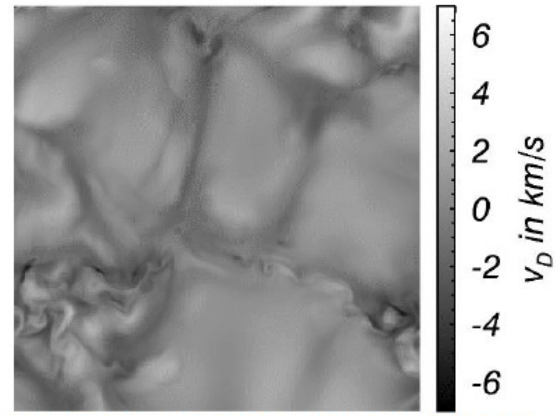
Area size on the solar surface: 5000km x 5000km

MHD simulations and line synthesis: J. M. Borrero, B. W. Lites, A. Lagg, R. Rezaei, and M. Rempel. Comparison of inversion codes for polarized line formation in MHD simulations. I. Milne-Eddington codes. Astronomy and Astrophysics, 572:A54, December 2014



2D simulation procedure

Ideale Karten

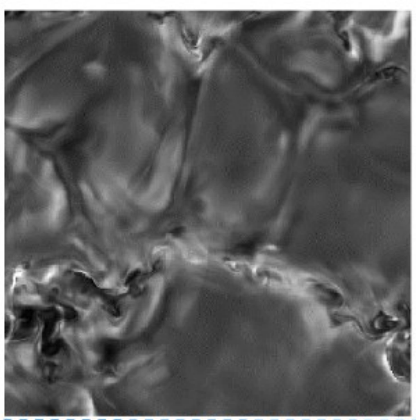


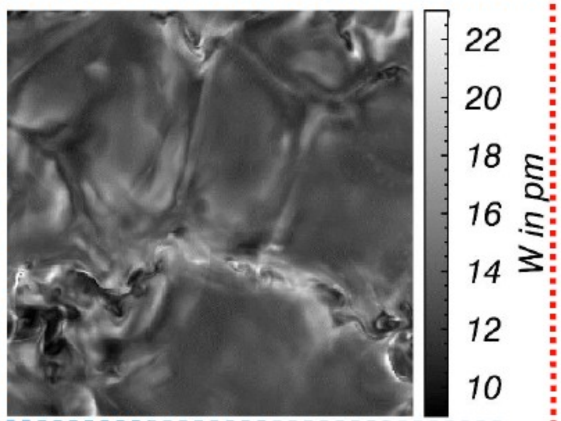
on

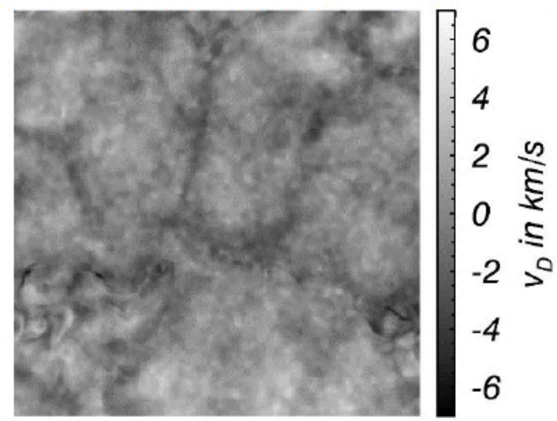
3

Intensit

I_0 , I1 , I2 ,

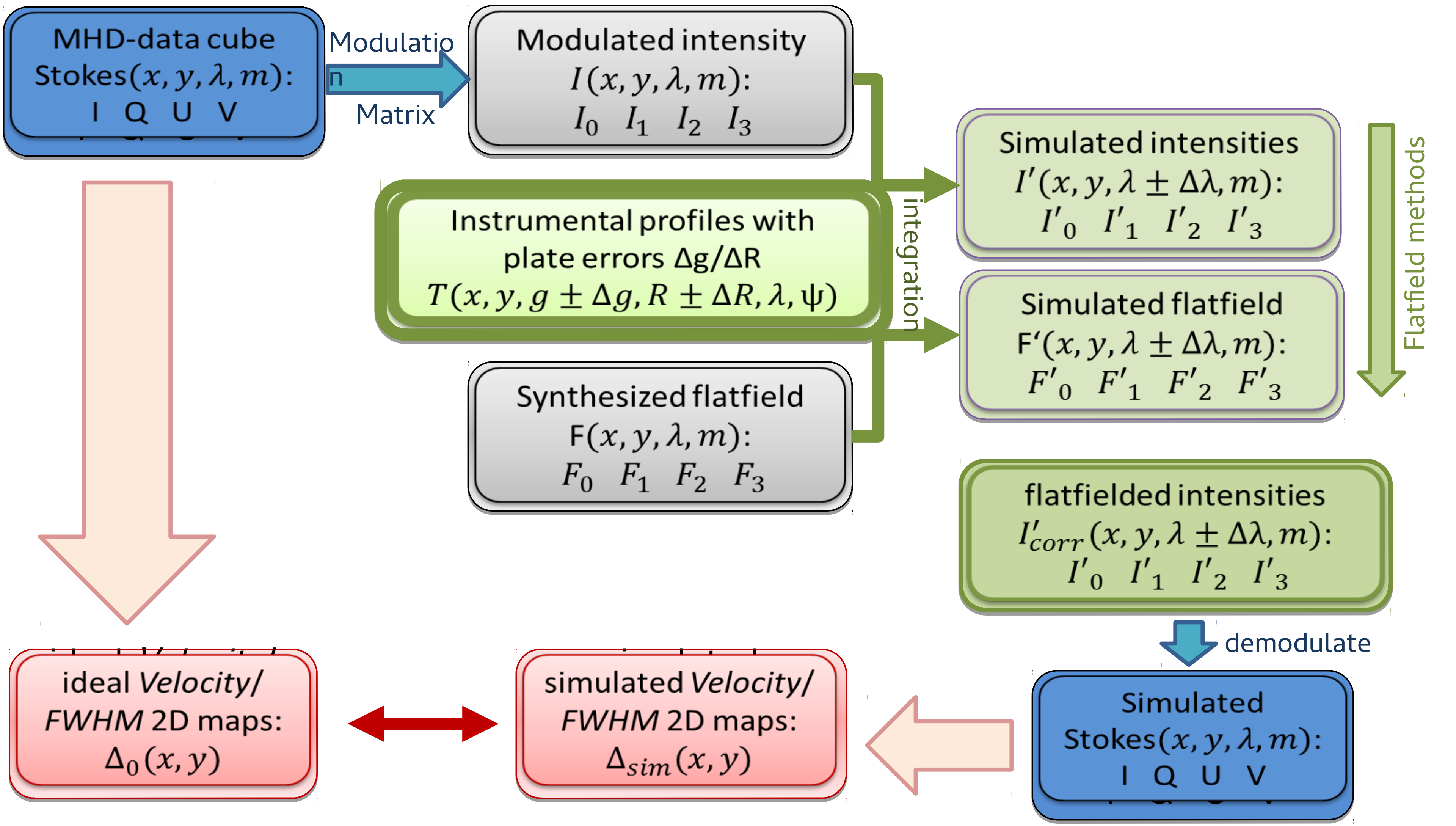






2D Simulations procedure with MESA

Multi Etalon Simulation Algorithm



2D-Simulations – micro roughness

Microroughness: measured with a HeNe laser at VTT/TESOS (testbench) with similar setup

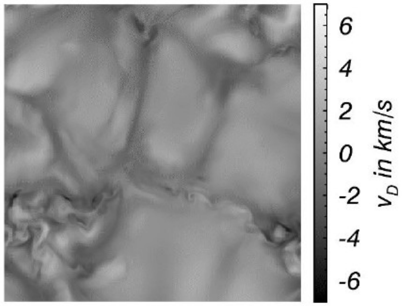
Errors in Doppler velocity, full width half maximum and loss of photon flux for the instruments

FPIs mounted near the focal plane

Doppler velocity maps

λ_0=630.25nm - Δgrms = 2.5nm

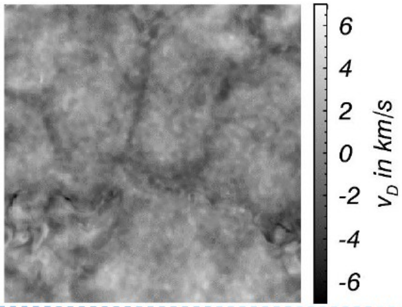
Ideal map



High resolution mode

Instrument 1 (Triple)

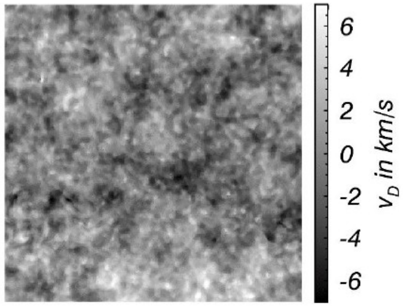
$\Delta\lambda$ = 3.8pm



Fast scan mode

Instrument 2 (Double)

$\Delta\lambda$ = 6pm



Questions:

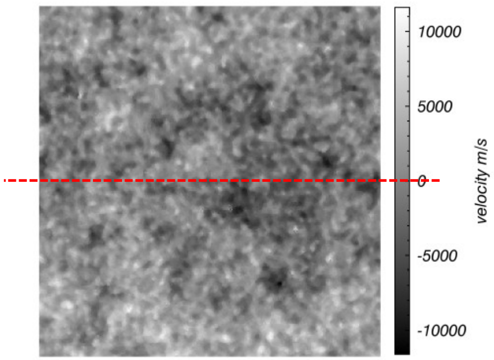
What are the error contributions for a multi-FPI-system with realistic plate error distributions?

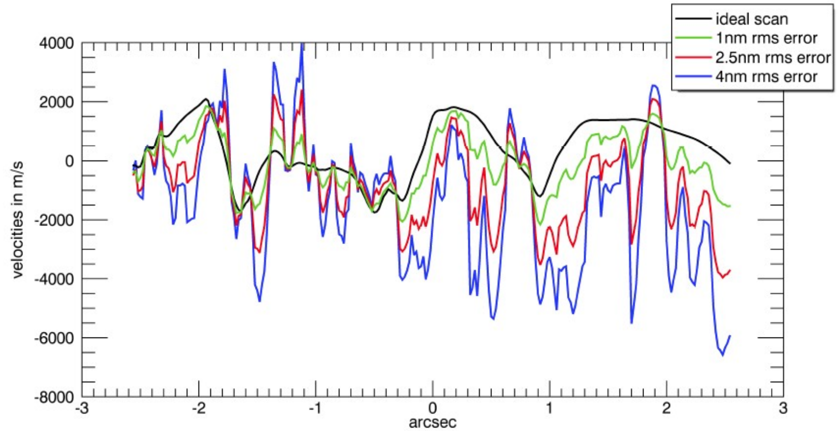
Does a defocused mounting of the FPIs in the optical path reduces the errors?

Is it possible to calibrate the induced errors?

Illustration of the effect of a defocused mounting

Mounting near focal plane

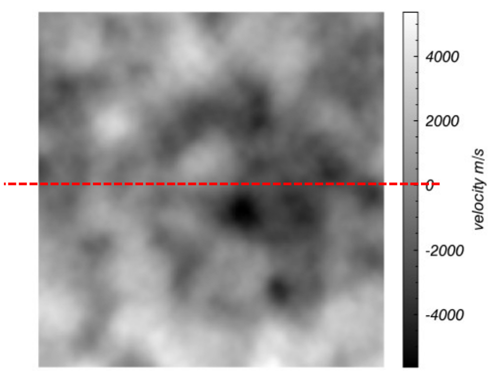


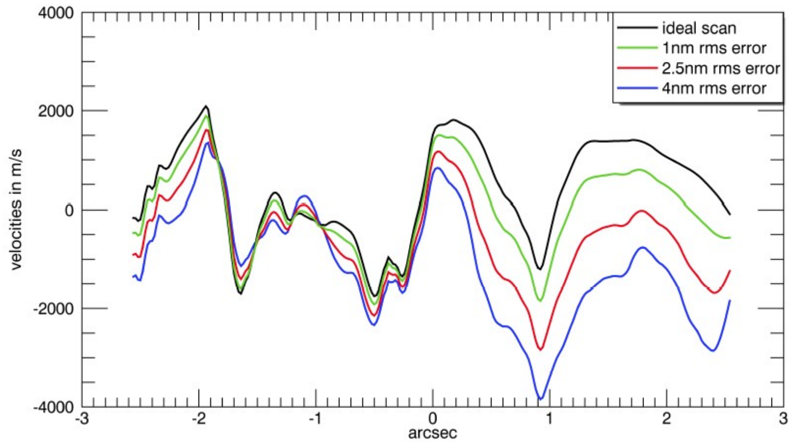


2D Doppler maps

Resulting velocities for a micro roughness

Defocused mounting



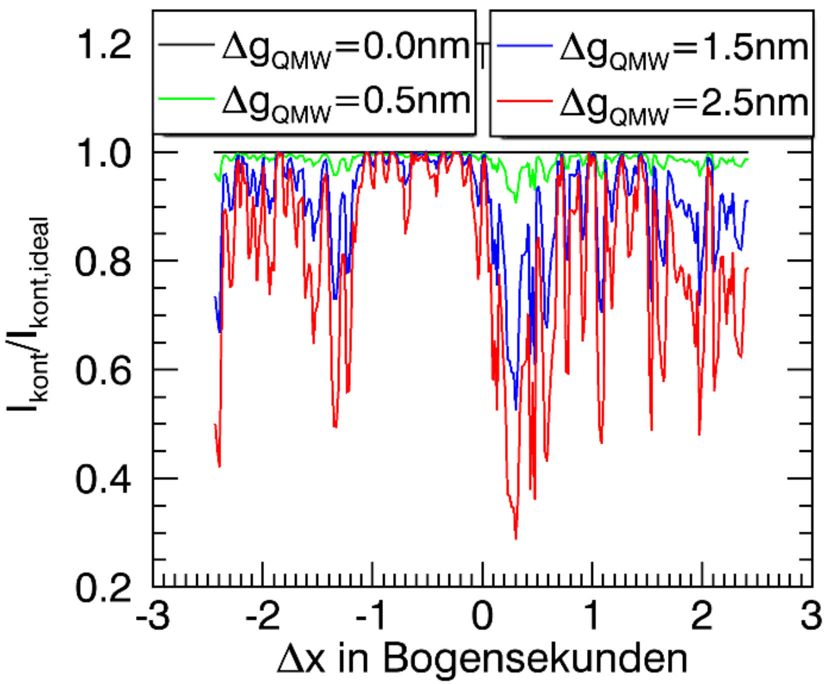


Simulated observations for different mountings of the FPI

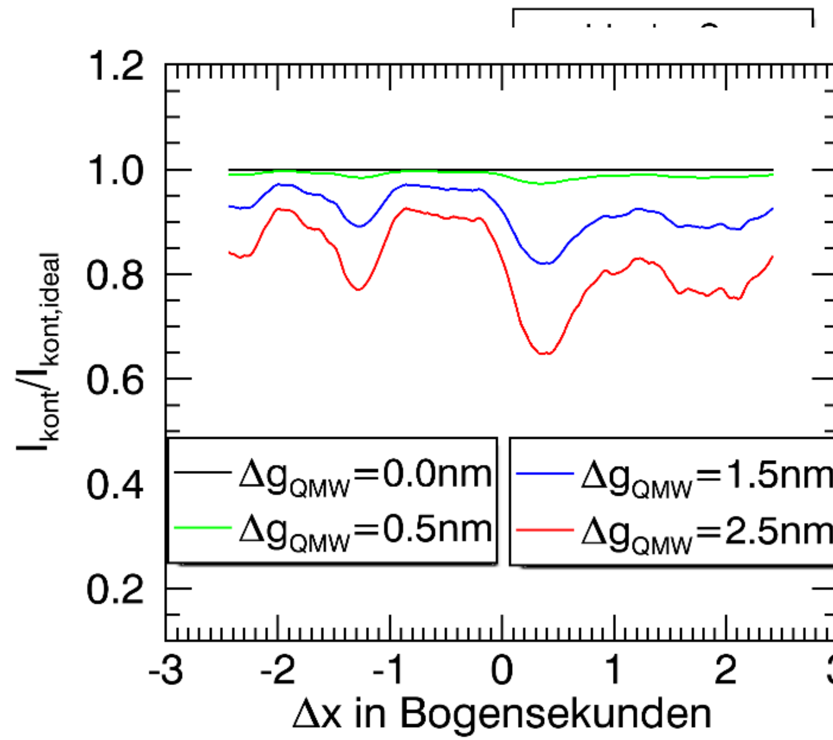
Slices through the middle for a simulated FOV of 5″ are shown for Instrument 2

- spectral resolution 100.000@500nm -

Near focal plane



Defocused mounting

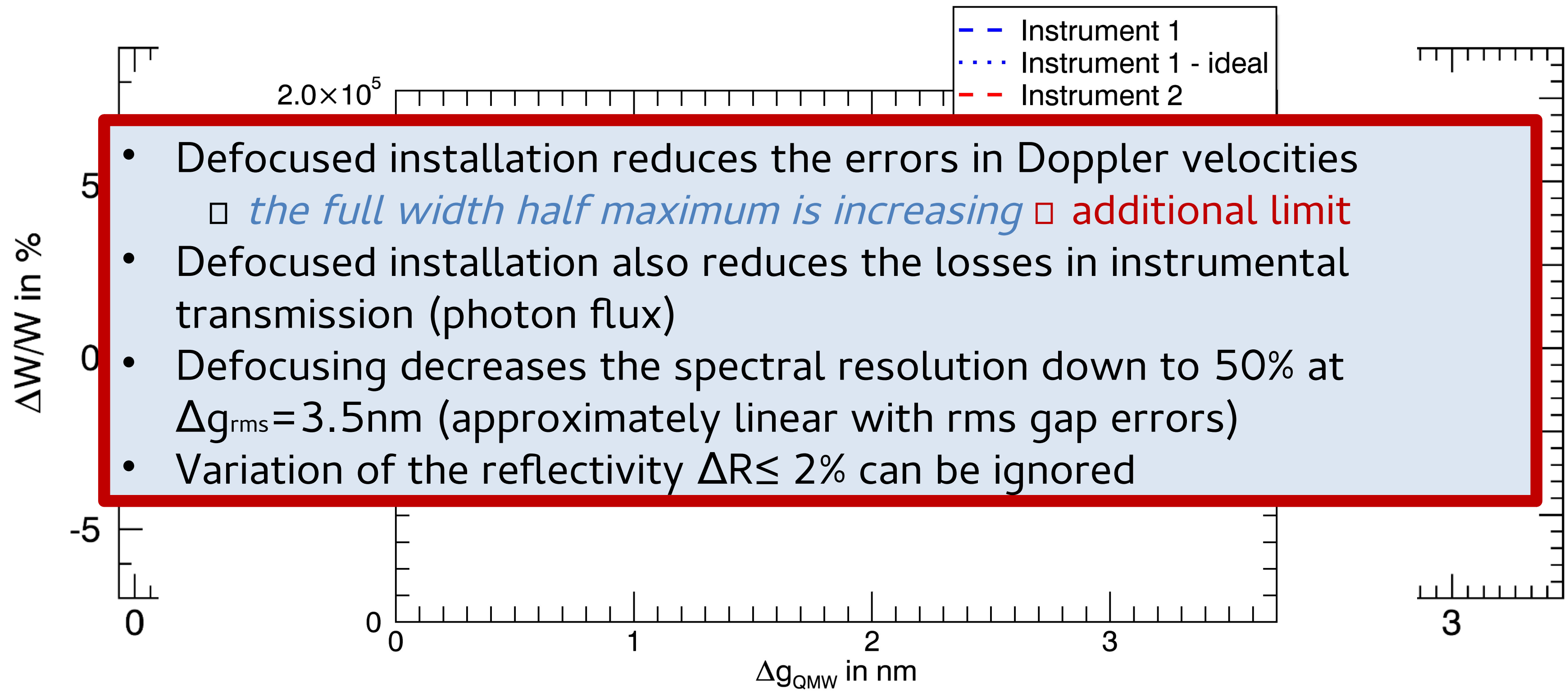


Results for micro roughness

Shown are the rms values for the simulated field of view

near focal plane

defocuse

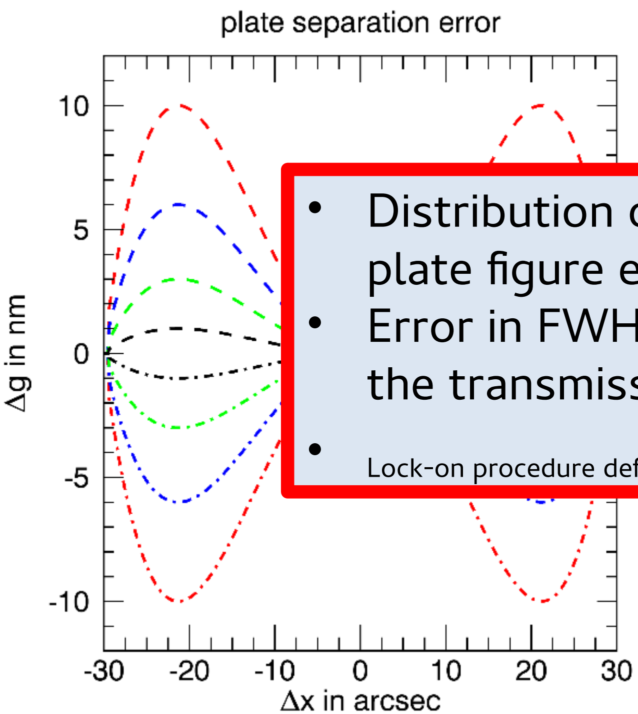


- Defocused installation reduces the errors in Doppler velocities
  - *the full width half maximum is increasing* □ additional limit
- Defocused installation also reduces the losses in instrumental transmission (photon flux)
- Defocusing decreases the spectral resolution down to 50% at Δg_{rms}=3.5nm (approximately linear with rms gap errors)
- Variation of the reflectivity ΔR≤ 2% can be ignored

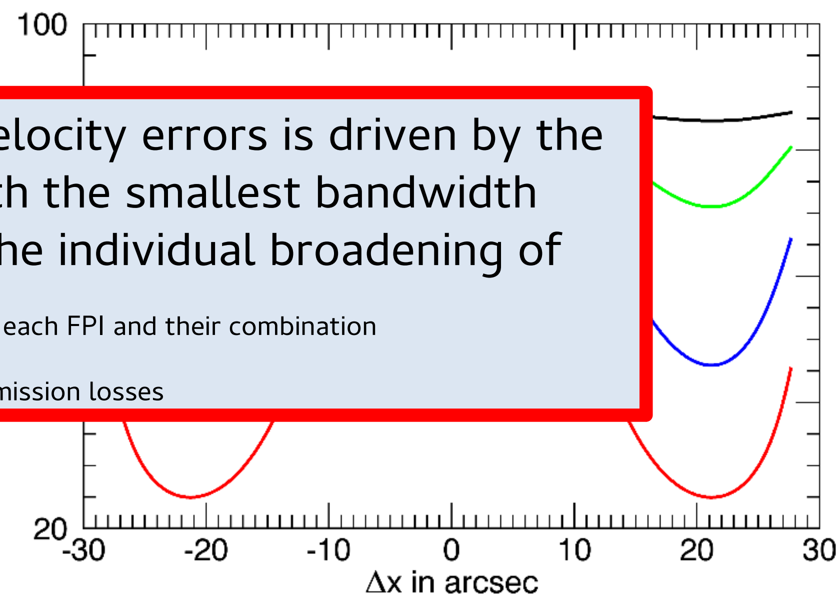
Transmission losses for plate figure errors

For one resolution element, the error stays constant → $\Delta g(\theta)|_{x,y}=\Delta g|_{x,y}$ and $\Delta R(\theta)|_{x,y}=\Delta R|_{x,y}$

Shown are the total instrument transmissions T for a slice through the middle of a simulated FOV=60″



- Distribution of the introduced velocity errors is driven by the plate figure errors of the FPI with the smallest bandwidth
- Error in FWHM is originated in the individual broadening of the transmission profiles $T_{i\,(x,y)}$ for each FPI and their combination
- Lock-on procedure defines the distribution of the transmission losses



Results for simulated plate gap errors

	FPI mounting	$\Delta v_{D,rms}$ / nm	$\sigma_{\Delta v_D}$ / nm	ΔW_{rms} / nm	$\sigma_{\Delta W}$ / nm
Instrument 1	focus	335 m/s	36 m/s	1.0 %	1.6 %
	defocus	235 m/s	54 m/s	$0.2\% \cdot \Delta g + 0.8\% \cdot \Delta g^2$	1.0%
Instrument 2	focus	685 m/s	50 m/s	0.8 %	2.0 %
	defocus	457 m/s	14 m/s	$1.8\% \cdot \Delta g + 1.2\% \cdot \Delta g^2$	1.0%
	defocus, figure	564 m/s	43 m/s	0.3 %	1.9 %

Magnetic sensitivity – 1D Simulation

- Photon noise n=$\sqrt{N_{ph}}$
  - transmission of the instrument, telescope and all the optical parts (telescope, Coudé-table and polarizing beamsplitter t=0.17)
  - efficiency of the detector e=0.56
  - exposure time t=25ms

→ Instrument 1: SNR=N_{ph}/n=560

→ Instrument 2: SNR=710

- Inversion code **SIR** for line synthesis and inversion

  B. Ruiz Cobo and J. C. del Toro Iniesta. Inversion of Stokes profiles. The Astrophysical Journal, 398:375–385, October 1992. doi: 10.1086/171862

  - atmosphere model: HSRA
  - Fe I 630.25nm: line synthesis for different magnetic field strengths and inclinations

Instrument 1: SNR=N_{ph} /n=560
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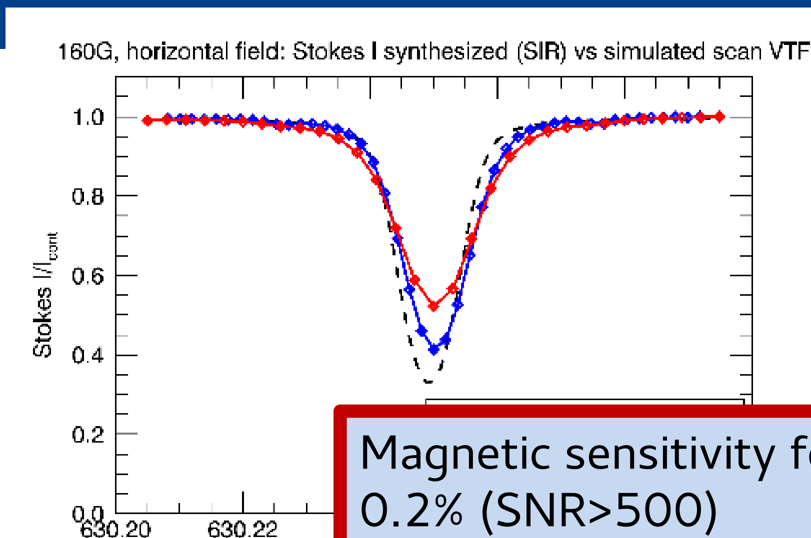
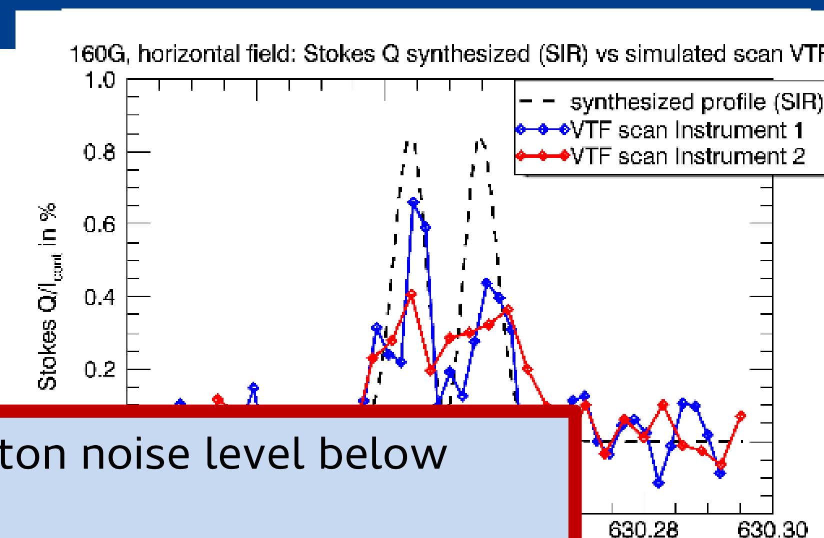
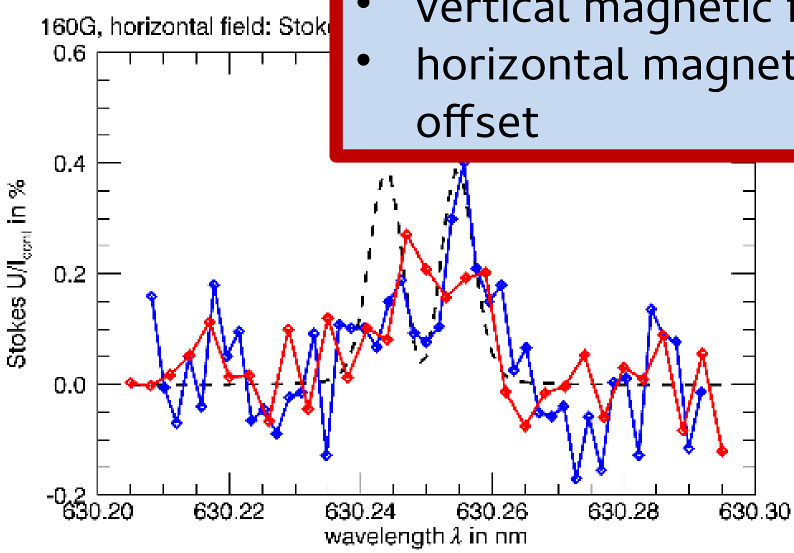
Fe I 630.25nm: line synthesis for different magnetic field strengths and inclinations

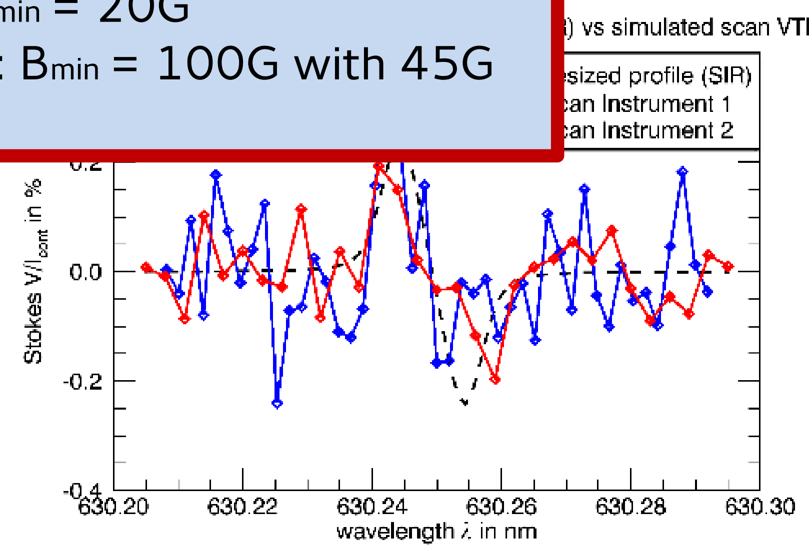
Simulations for a horizontal magnetic field vector

Full Stokes vector I, Q, U and V is shown









Magnetic sensitivity for photon noise level below 0.2% (SNR>500)

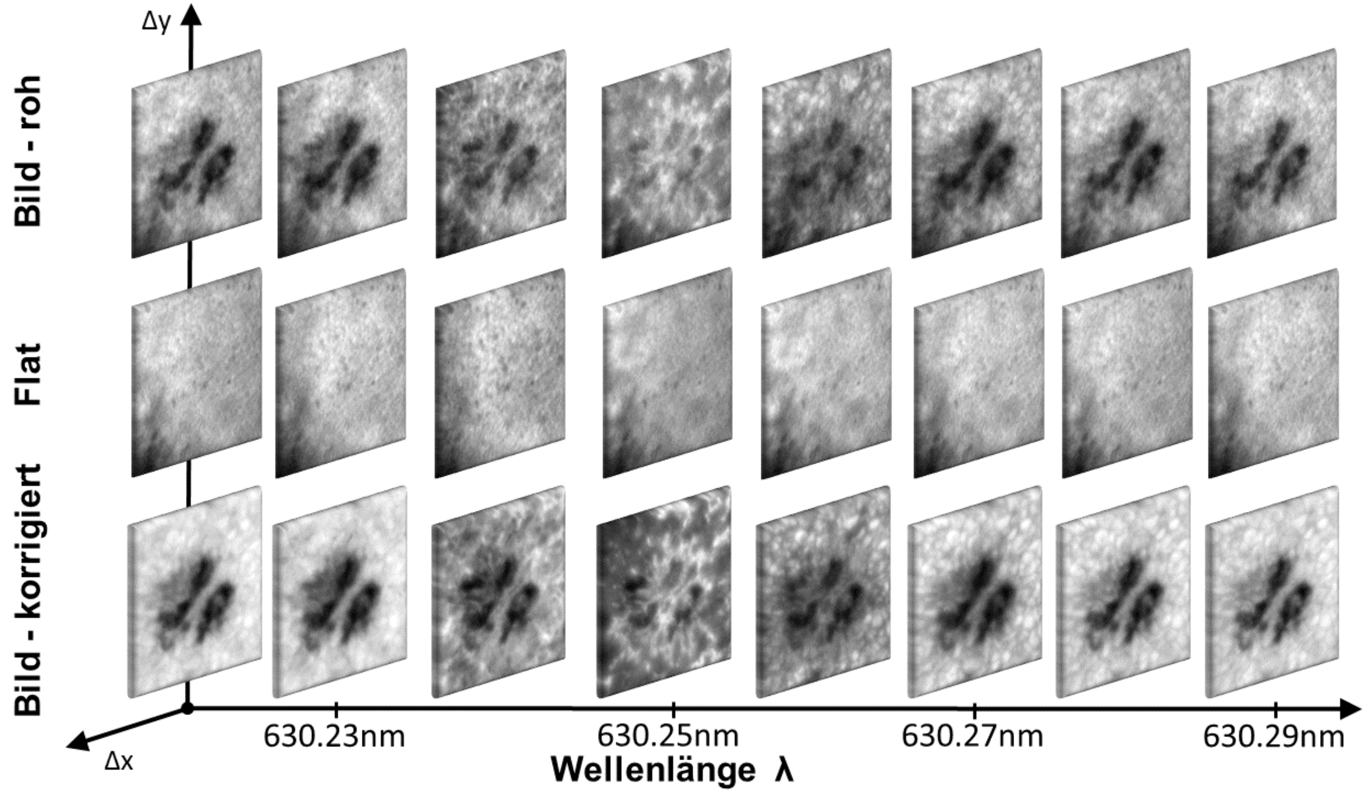
- vertical magnetic fields: B_{min} = 20G
- horizontal magnetic fields: B_{min} = 100G with 45G offset

Data calibration

Enhancement of the standard procedure – shown for instrument 2 in Tandem configuration in a defocused mounting of the FPI on the optical axis

Standard method for 2d image calibration

 The error in the contrast is corrected very well



Problem for solar spectroscopic observations: calibrating the data will introduce additional errors in terms of shifting the line profile and broadening the FWHM in an uncontrolled way

Flatfield methods

Three flatfield approaches and their differences

Calculate the gain table

$$\mathrm{Gain}_0(x,y,\lambda) = \frac{[\mathrm{Flat}(x,y,\lambda) - \mathrm{Dark}(x,y)]}{\langle[\mathrm{Flat}(x,y,\lambda) - \mathrm{Dark}(x,y)]\rangle}$$

$$\mathrm{Gain}_1(x,y,\lambda) = \frac{[\mathrm{Flat}(x,y,\lambda) - \mathrm{Dark}(x,y)]}{\langle[\mathrm{Flat}(x,y,\lambda) - \mathrm{Dark}(x,y)]\rangle|_{\pm\Delta\lambda(x,y)}}$$

$$\mathrm{Gain}_2(x,y,\lambda) = \frac{[\mathrm{Flat}(x,y,\lambda) - \mathrm{Dark}(x,y)]}{\langle[\mathrm{Flat}(x,y,\lambda \pm \Delta\lambda(x,y)) - \mathrm{Dark}(x,y)]\rangle}$$

Determined 2D map of introduced shifts in line core position μ_0

Correct the data

$$I'(x,y,\lambda) = \frac{[I_0(x,y,\lambda) - \mathrm{Dark}(x,y)]}{\mathrm{Gain}(x,y,\lambda)}$$

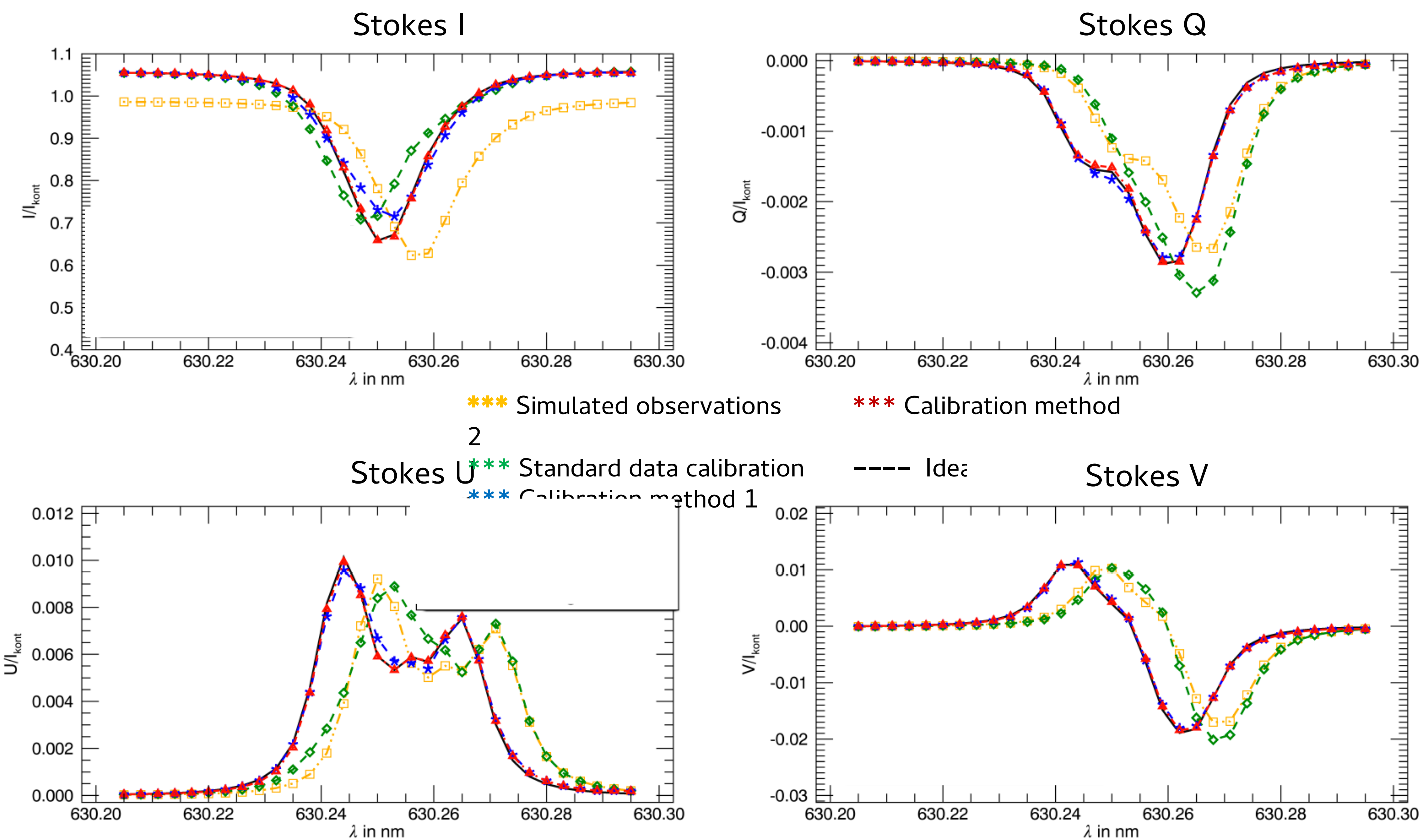
Calculate i.e. the Doppler velocity maps $v_{D(x,y)}$

$$\Delta\lambda_\mathrm{D}(x,y) = \Delta\lambda'_\mathrm{D}(x,y) \pm \Delta\lambda(x,y)$$

$$v_D(x,y) = \frac{\Delta\lambda_\mathrm{D}(x,y)}{\lambda_0} \cdot c$$

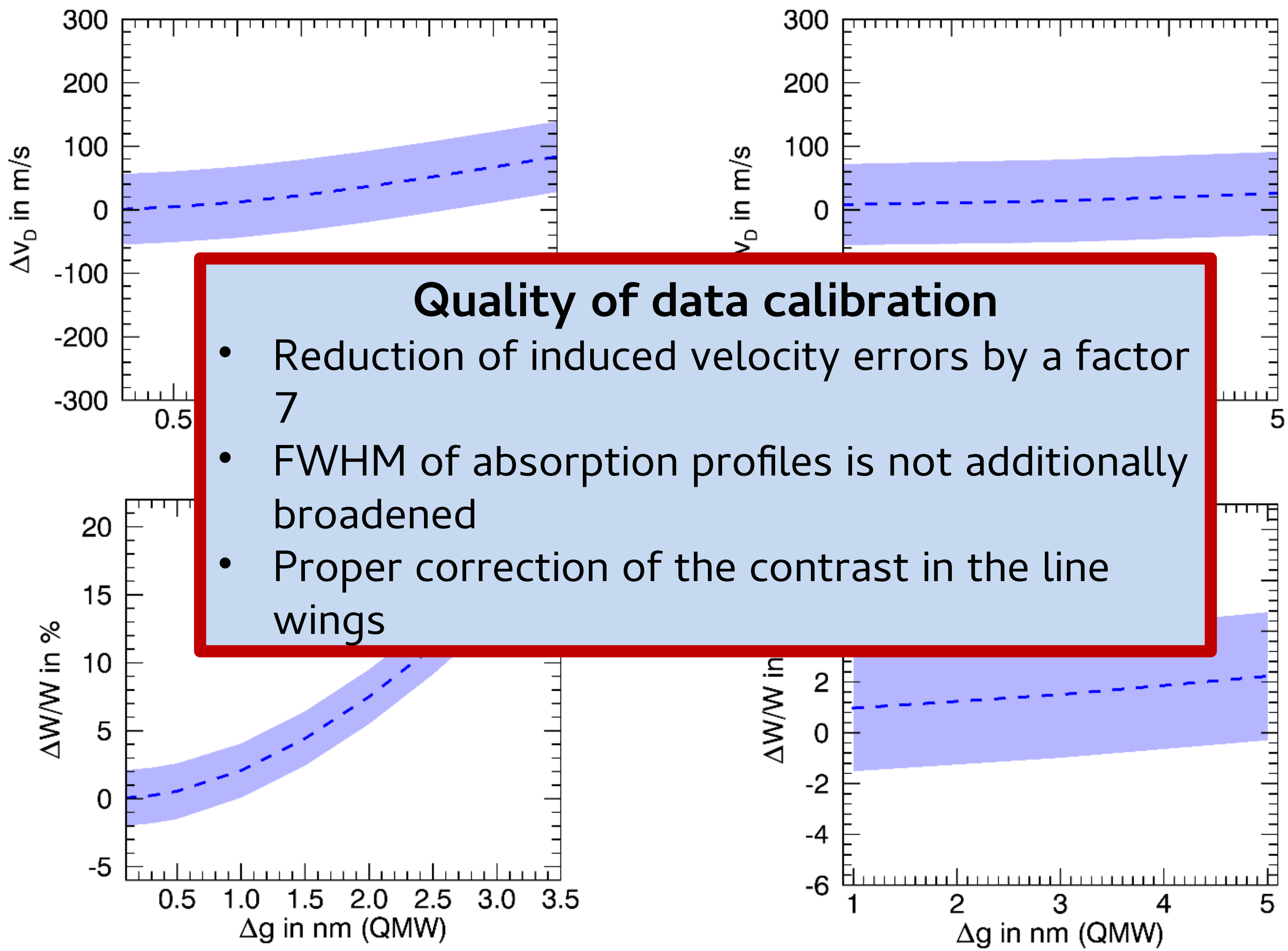
Differences in calibration methods

The calibration methods are illustrated for a full Stokes vector I, Q, U and V with a plate gap error Δg_{rms}=3nm



Data calibration and the benefit on physical measurements
- Calibration method 2 -

Micro roughness | Plate figure errors



Quality of data calibration

- Reduction of induced velocity errors by a factor 7
- FWHM of absorption profiles is not additionally broadened
- Proper correction of the contrast in the line wings

Consequences for the VTF

Instrument 1 or Instrument 2

We will realize instrument 2 in tandem configuration for the VTF:

Defined values for the manufacturing process to achieve the demanded measurement accuracy

Error distribution	Surface error Δr (rms) Reflectivity error ΔR (rms)
Micro roughness	Δr ≤ 0.5nm
	ΔR ≤ 2%
Plate figure errors	Δr ≤ 5nm
	ΔR ≤ 2%

- Minor losses in the photo[n] … individual transmission pr[o] … element
- The higher induced velocit[y] … well with the shown data
- Demanded magnetic sensi[tivity] … velocity measurements and the FWHM is fulfilled
- Shorter cadence for line acquisition due to lower spectral resolution

Thank you for your kind attention!

Questions?