Prototype characterization and future development of the Fast Solar Polarimeter

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The need of high-cadence polarimeters

- To study small-scale and faint $\vec{B}$ → Spectropolarimetric data with both high **spatial resolution and sensitivity**

- **Ground based measurements** can benefit from **large apertures** and relax the sensitivity vs resolution tradeoff that arises when measuring dynamic solar features

- However ground based measurements suffer from seeing which **reduces spatial resolution** and also introduces **polarimetric artifacts**

Why we need high-cadence polarimeters ?

Mainly to **fight the seeing effects on polarimetry** and make full use of next-generation, large-aperture solar telescopes

The need of high-cadence polarimeters

1. To optimally implement image restoration:

   - Short exposure times to "freeze the atmosphere" $(\sim 10\ ms)$
   - High duty cycle to reduce the effects of solar evolution $(\sim 100\ \%)$

   } $\mathbf{FR > 100}\ \boldsymbol{fps}$ **Low camera noise!**

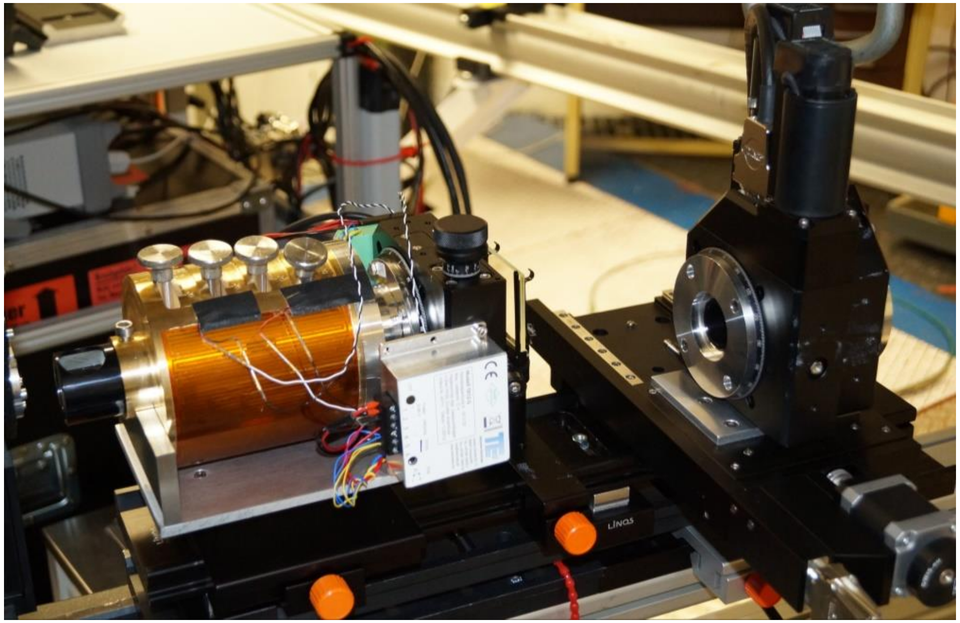
2. Reduce seeing induced polarimetric artifacts (SIC) when using temp. modulation:

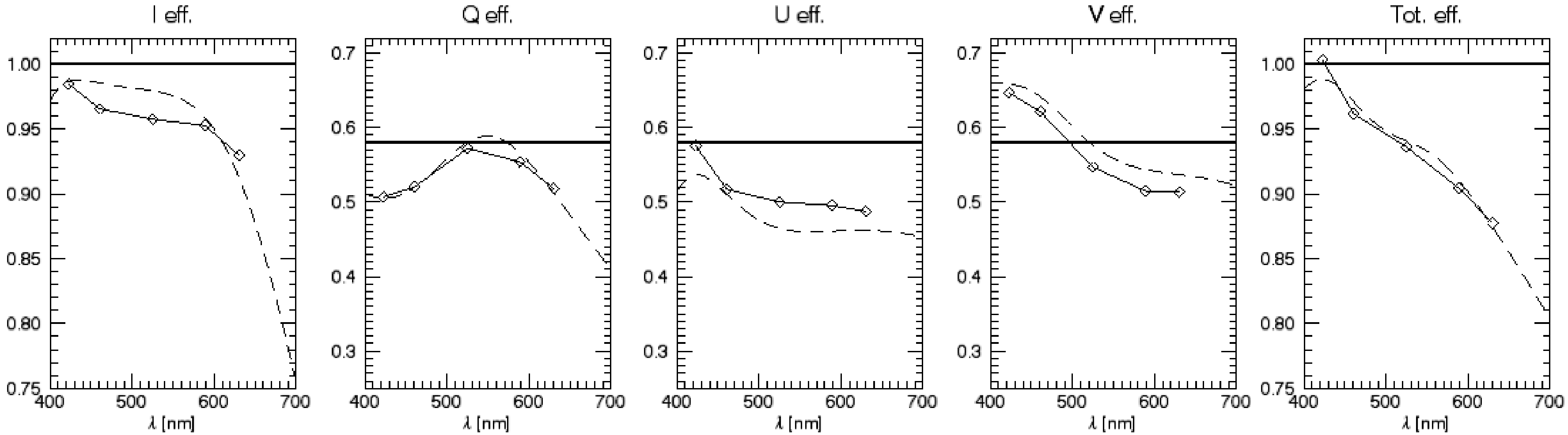
   - In single beam, **Krishnappa and Feller (2012)** showed that acquiring a full meas. in $\sim 10\ ms$ → SIC $\sim 10^{-4}$
   - In a Dual beam also reduces SIC from V → Q, U

   } $\mathbf{Mod.\ freq.\ \sim 100}\ \boldsymbol{Hz}$

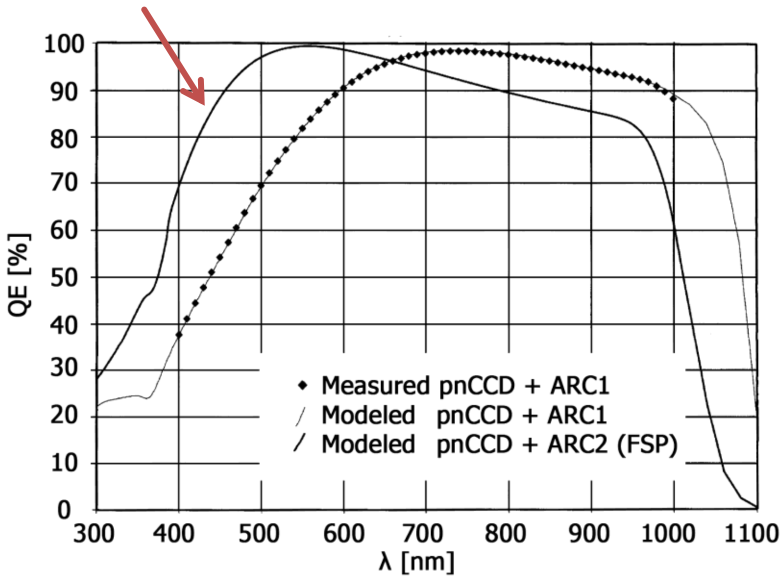
	Scheme	Modulator	Camera
FSP (2011-2015) **Iglesias et. al. 2016**	Single beam	Full-Stokes, FLC-based, achromatic modulator **(200 Hz)**	Custom-made 264x264 pnCCD **(800 fps)**
FSPII (2015->)	Dual beam on one sensor with a novel pol. beam splitter	same **(100 Hz)**	Custom-made 1kx1k pnCCD **(400 fps)**
CMOS application by M. van Noort et. al. (2016 ->)	Dual beam on two sensors	same (25-100 Hz)	Fast CMOS cameras (400 fps)

- Similar to the SOLIS/VSM modulator **(Keller et al. 2003)**
- 2 FLC's + 2 static retarders + Pol. Beam Splitter
- Broadband efficiency optimized from 400 to 700 [nm] **(Gisler 2005, Iglesias et. al. 2016)**

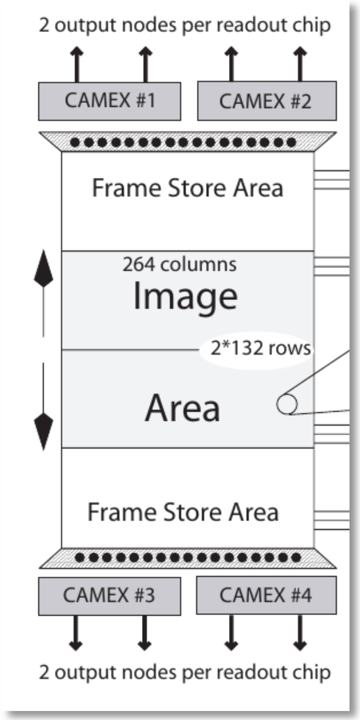


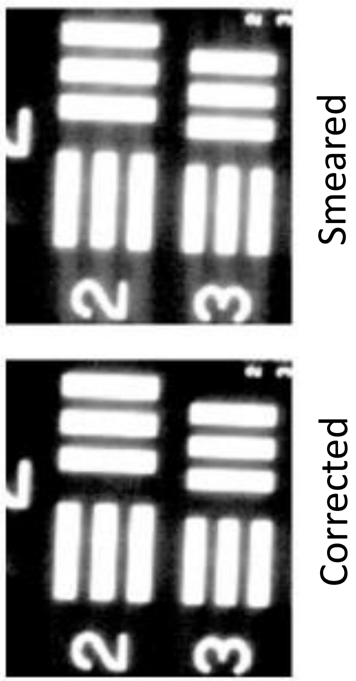


1. Small **(264x264**) and back-illuminated **(FF=100%)**
2. Custom made pn-type CCD sensor (pnCCD)
   - High QE: **>90% from 460 to 800 nm**
   - Low read out noise: **4.9** e^{-}
3. Parallel channel readout
   - Frame rate **400 fps** (up to 800)
4. Split frame transfer
   - DC~**98%**
   - **No shutter** (numeric smearing correction)



pnCCD sensor

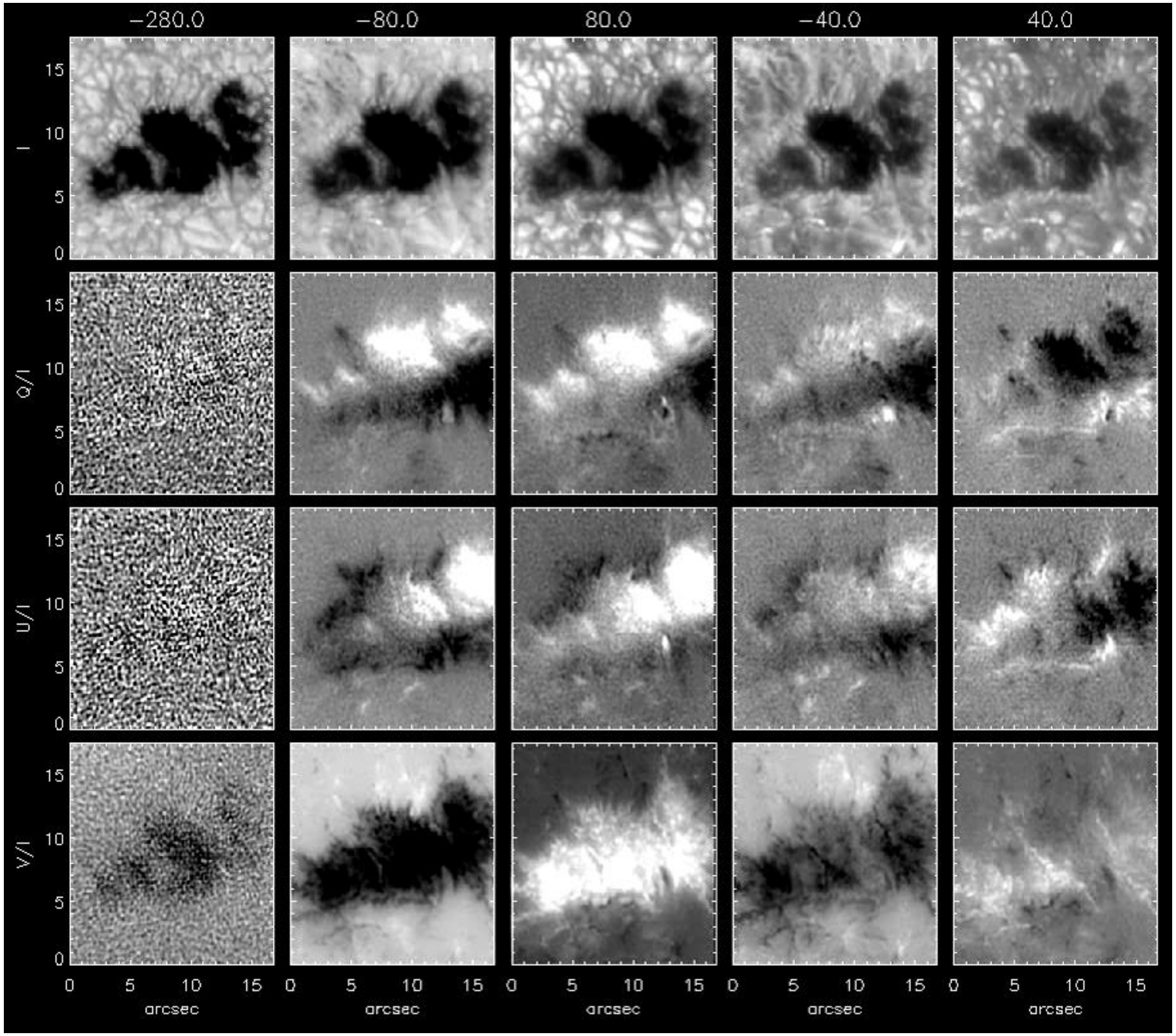




Iglesias et. al. 2015

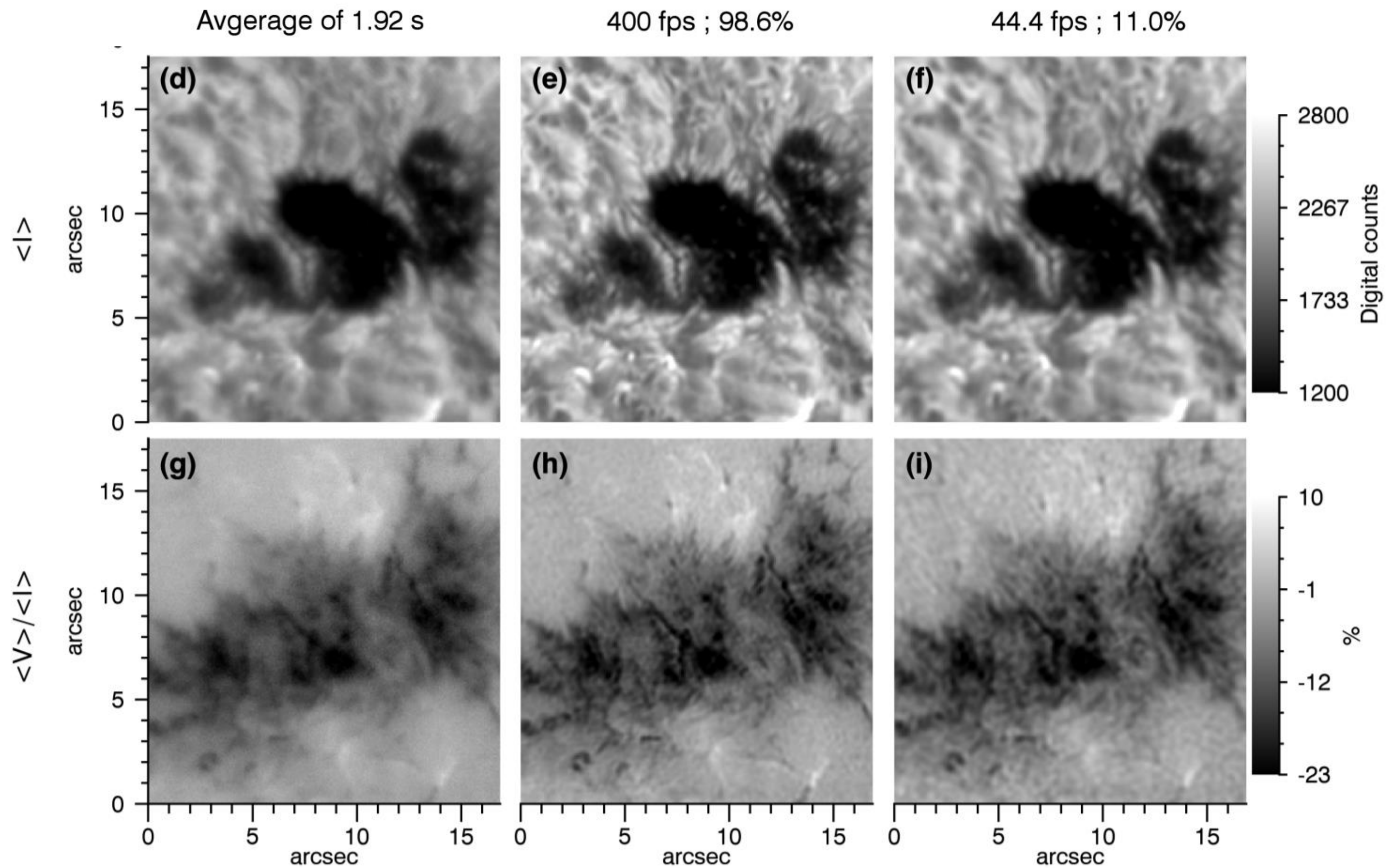
TESOS Filtergraph

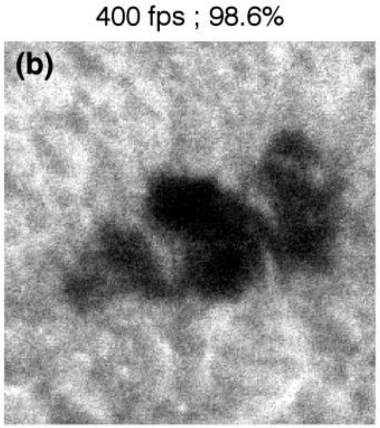
Strong Zeeman signals with high-cadence: (MOMFBD restored, **Van Noort et. al. 2005**)



Line:	Fe I 630.2 nm
Gray scales:	$\pm 8\%, \pm 8\%, \pm 16\%$
Cont. gray scales:	$\pm 0.8\%, \pm 0.8\%, \pm 1.6\%$
Noise in continuum:	$\sim\mathbf{0.35\%}$
Int. time per point:	$\mathbf{1.89}\ \boldsymbol{s}$
Wall time per point:	3.04 s
Spatial sampling:	0.08 arcsec/pixel
Spectral sampling:	21 mA/pixel
FOV:	19.7x20.4 arcsec^2

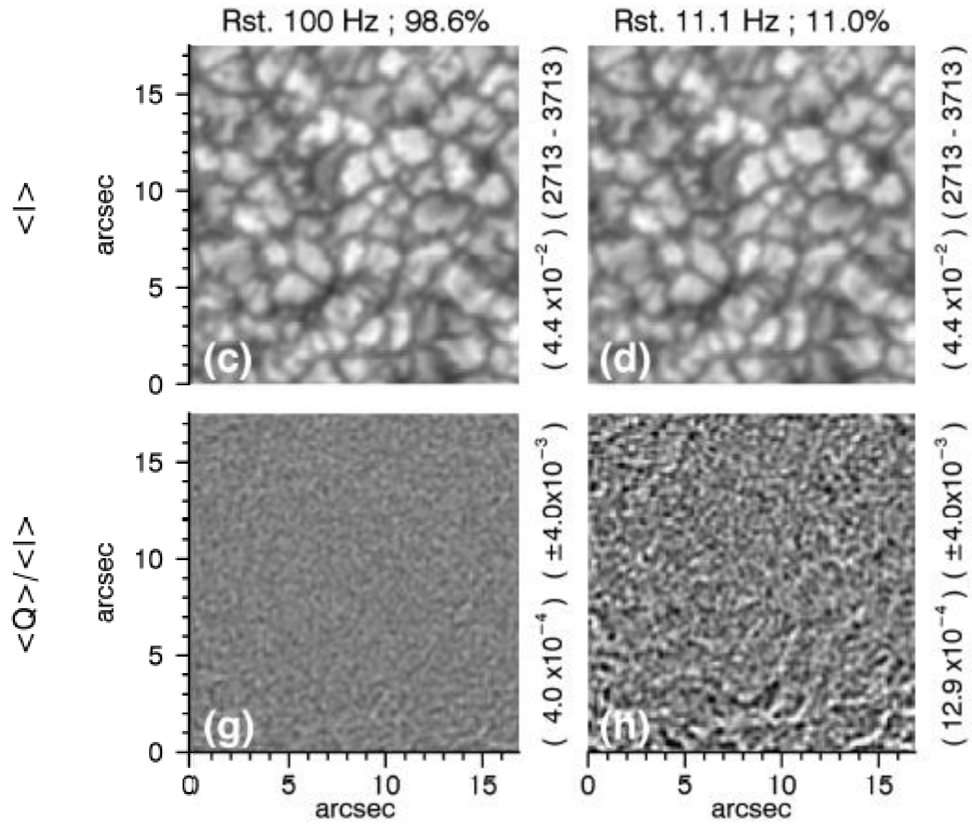
Benefits of large number of frames in MFBD





Single frame

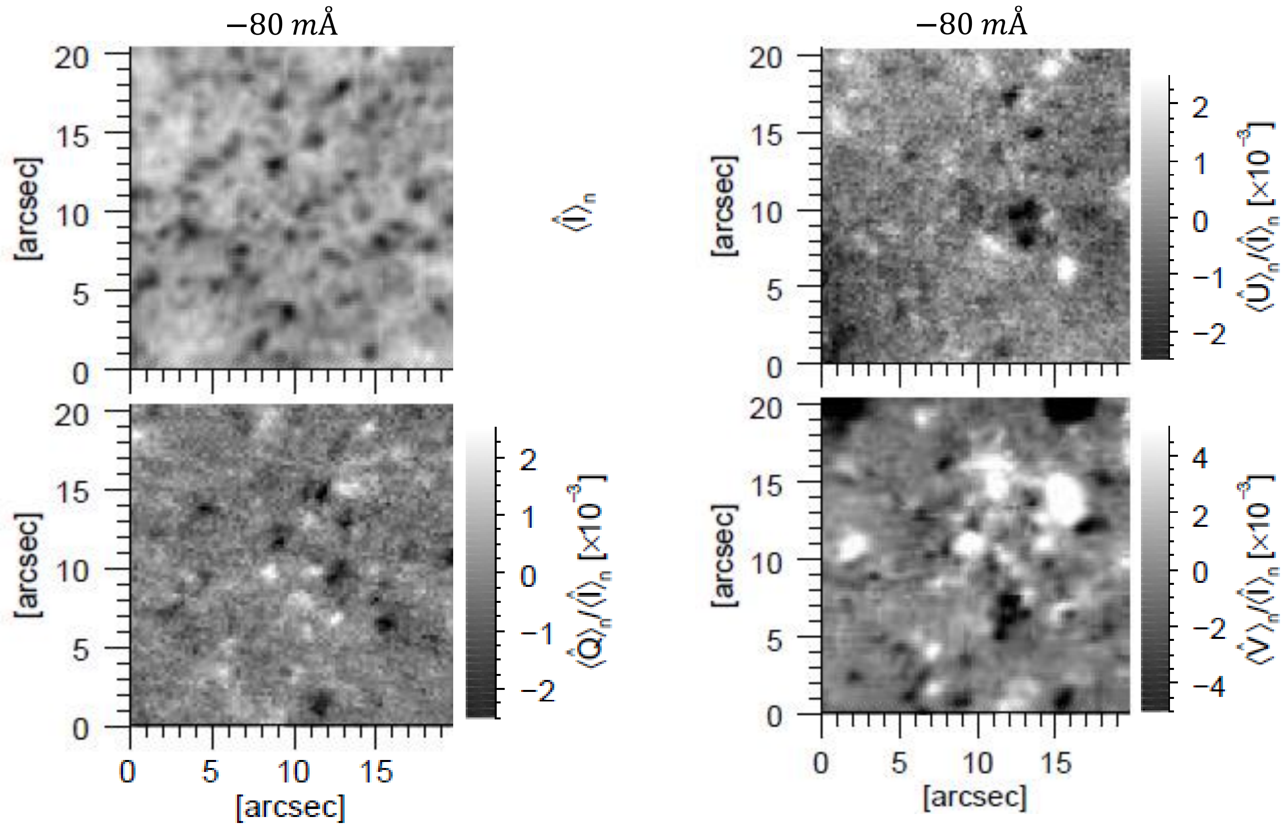
Seeing induced crosstalk in non-mod filtergrams



1.16 min MOMFBD restored

TESOS Filtergraph

Low noise Zeeman signals in Fe I quiet Sun:



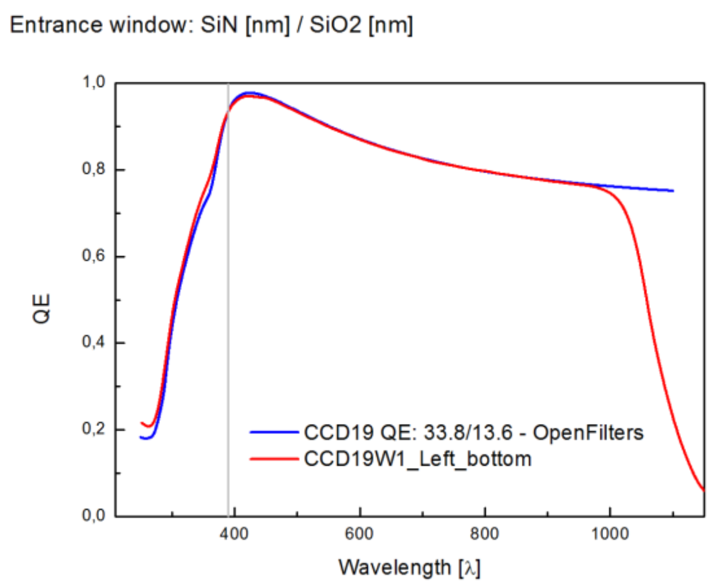
Line: Fe I 630.2 nm ; Int. time 0.95 min ; Wall time 3.99 min ; FOV 19.7x20.4 arcsec^2 ; 3x3 Binned
Spatial sampling **0.24 arcsec/pixel** ; rms **noise in Q/I is 0.03%** ; Spect. sampling **21 mÅ**

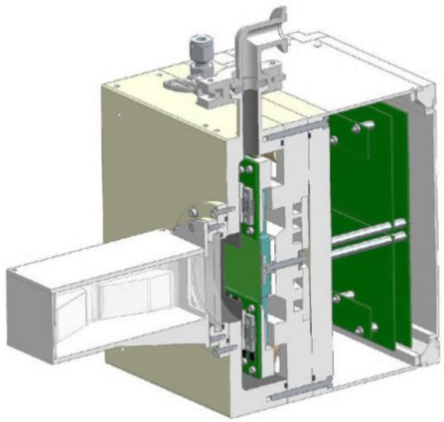
FSPII

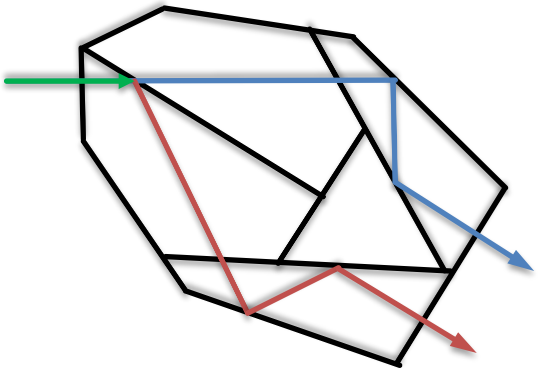
1. New custom-made pnCCD camera that keeps the low noise **(4.9 e⁻)** while having 16 times larger area **(1024x1024).** Also has better QE in the blue, e.g. **at 400 nm from 70% to 94%**

2. Dual beam on a single sensor, to double photon efficiency and reduce I → Q,U,V crosstalk, **using a novel polarizing beam splitter** (M. van Noort and A. Feller).

   - Made of Fused silica to work between 390 and 860 nm
   - Both paths are identical (2 total internal reflections) to minimize beam imbalances
   - The normal refractions at the entrance and exit faces minimizes dispersion.







Frist Light 2017!

Some lessons learned

- ✓ Efficiencies optimization worked well $\rightarrow$ **Total eff. >90%** (400 to 600 nm)
- ✓ The **high QExFF, DC and low noise** of the pnCCD camera proved key to detect faint signals in low flux lines and restore them using only the narrow band data.
- ✓ We preserved the high DC thanks to the **accurate numeric correction of the smearing**.
- ✓ A modulation frequency of **100 Hz strongly reduced SIC**, e.g. below the 0.02% noise for $\sim$1.16 min avg. of Fe I quiet-sun data.
- ✓ First light measurements
  - VTT SPECTROGRAPH/FSP $\rightarrow$ Second solar spectrum of Ca I with a noise of $\sim 0.008\%$
  - FSP+MOMFBD $\rightarrow$ Good to explore fast-moving (1s), small-scale (<1''), strong (~1%) signals.
  - TESOS/FSP $\rightarrow$ Sub-arcsec bipolar patches of linear pol. in the QS at the $\sim 0.1\%$ level
  - TESOS/FSP $\rightarrow$ First attempts to measure spatially resolved scattering polarization in Sr I (presented by Franziska Zeuner)