Contribution to Solar Brightness of small-size magnetic elements

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Abstract

Irradiance variability is mostly driven by surface magnetism, each magnetic feature contributing in a different manner. The contribution of small-size magnetic elements observed ubiquitously at high-spatial resolution on the solar photosphere, is still debated, as such features are mostly unresolved on full-disk images employed to model irradiance variability. Understanding the contribution to solar brightness of small-size magnetic elements, especially in quiet regions, will help understanding irradiance variability on the decadal and longer temporal scales, which, in turn, are fundamental to understand the role of the Sun on the Earth's climate. We present a preliminary study of the brightness of small-size magnetic elements using high-spatial resolution spectro-polarimetric observations acquired with the National Science Foundations Daniel K. Inouye Solar Telescope (DKIST) during Commissioning Phase 1. We focus on the Intensity contrast vs magnetic field relation, which is a fundamental observable in irradiance studies. Previous studies mostly focused on the FeI 630.1/630.2 nm spectral range and so to contextualize our results we focus here on this spectral region as well. By comparing DKIST results with MURaM magneto-hydrodynamic simulations, and with previous results published in the literature, we conclude that our results are in agreement with studies conducted on HINODE observations. We plan to extend the analysis to UV and IR ViSP observations and VBI blue continuum in order to better constrain the quiet sun contribution to spectral irradiance variations.

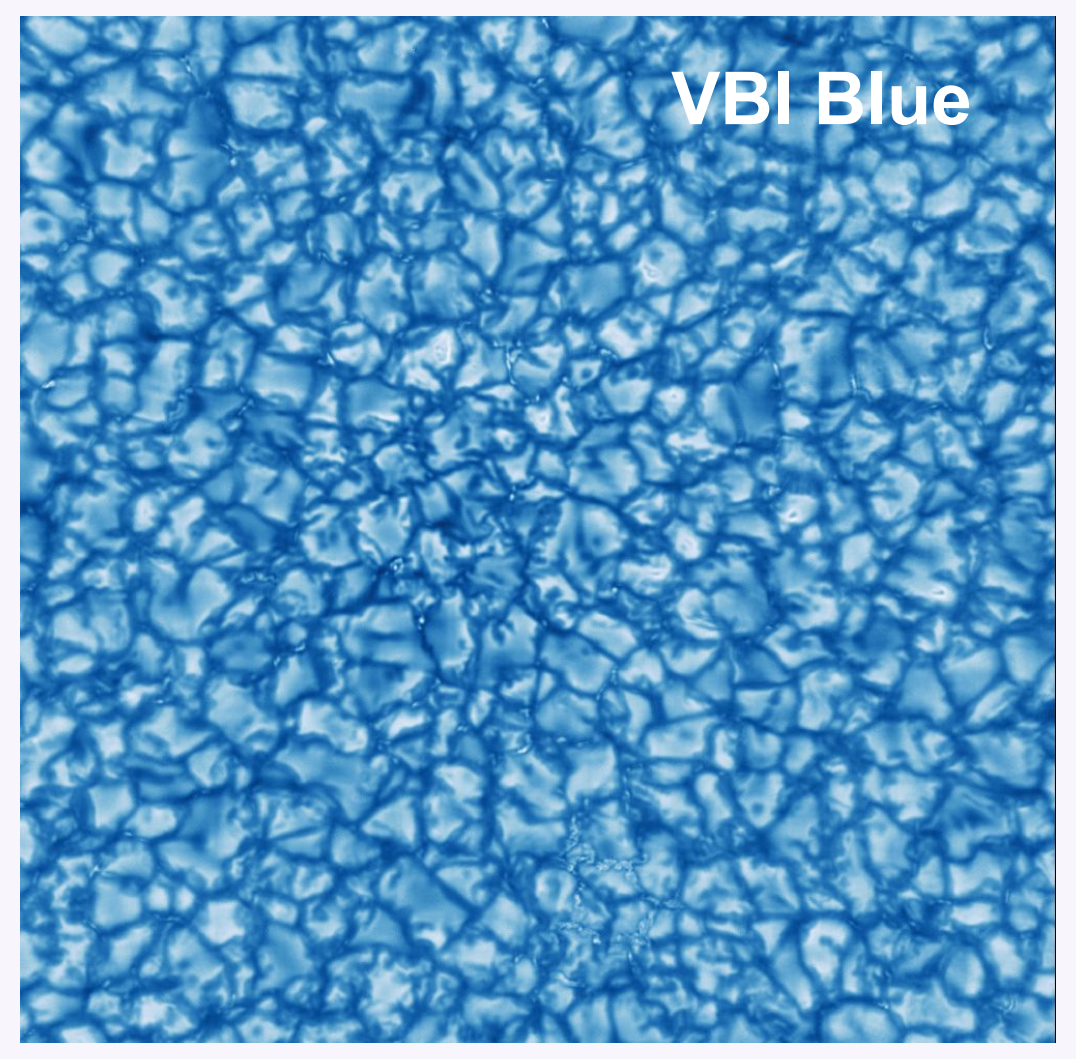
Data

DKIST Observations. Observations were acquired on July 7, 2022 during the DKIST Operations Commissioning Phase 1. Two very quiet regions were observed with the ViSP in the FeI 630.1/630.2 nm, CaIIH and Ca II 854.2 nm ranges and with the VBI blue continuum (450.4 nm). We present here results obtained from the preliminary analysis of data acquired in the FeI spectral range only.

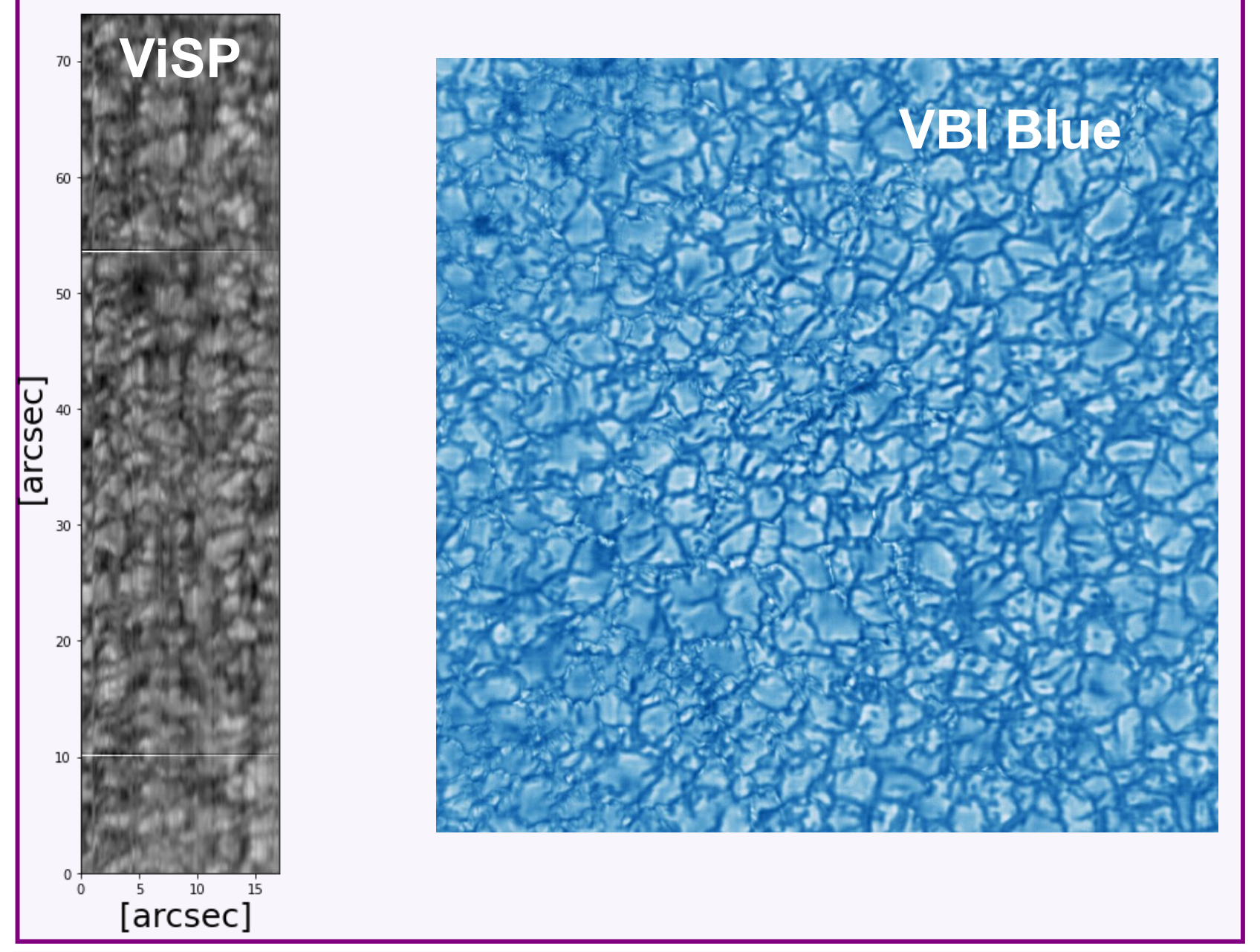
Seeing conditions were better during the acquisition of Target 2, therefore Target 1 was employed mainly for calibration purposes. By selecting a very quiet area in Target 1 we estimated:

Spectropolarimetric sensitivity = 0.001 x Ic
Cross talk I→V,Q,U = 0.00335, 0.00641 , -0.00335
Cross talk V→Q,U = 0.25, 0.25

Spectral resolution = 2pm
Scattered light level = 2% of Ic.

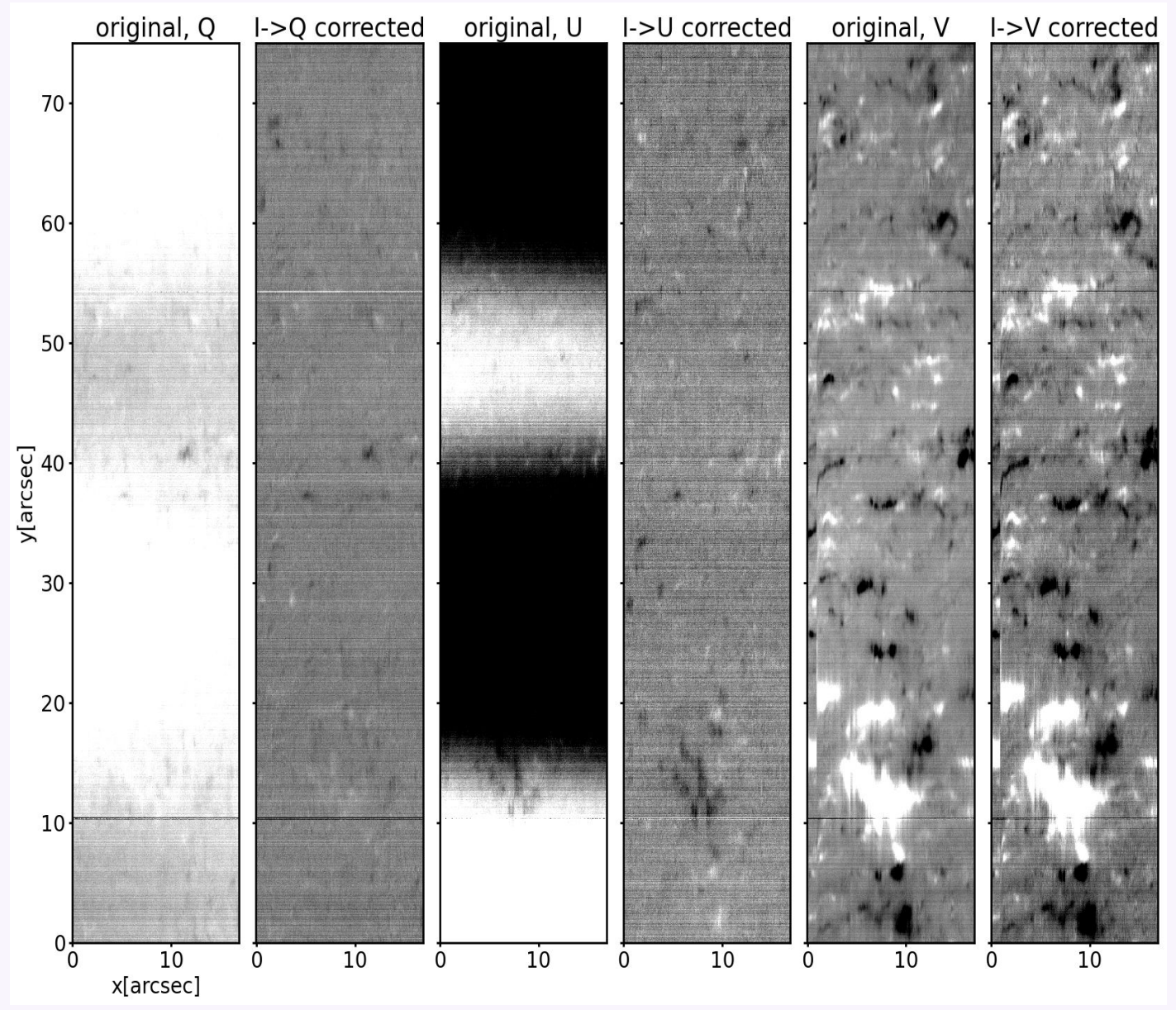


TARGET 2



Simulations. We use 30 snapshots from small local-dynamo simulations of the solar photosphere obtained with the Max Planck University of Chicago Radiative MHD (MURaM) code (Vögler et al.2005, Rempel 2020). The simulations cover an area of 9X9 arcsec, with a sampling of 10 km and the average magnetic field $\langle|Bz|\rangle_{\tau=1}$ = 45 G. Stokes parameters in the Fe I 630/1-630.2 nm lines were synthetized in NLTE using the RH code (Uitenbroek 2001) and emerging intensities were spatially degraded to the DKIST diffraction limit of 0.04 arcsec and resampled to the pixel/scale of observations.

Cross-Talk removal



Step 1: Compensate for cross-talk I-> Q,U,V

The cross-talk α from Stokes-I was estimated on a quiet region, under the assumption that continuum intensity of Stokes profiles, Ic, Vc, Qc and Uc are un-correlated:

$$\alpha_{I\to V}=\frac{V_C}{I_C} \qquad \alpha_{I\to Q}=\frac{Q_C}{I_C} \qquad \alpha_{U\to Q}=\frac{U_C}{I_C}$$

$$V_{corr1}=V-\alpha_{I\to V}*I$$

$$Q_{corr1}=Q-\alpha_{I\to Q}*I$$

$$U_{corr1}=U-\alpha_{U\to Q}*I$$

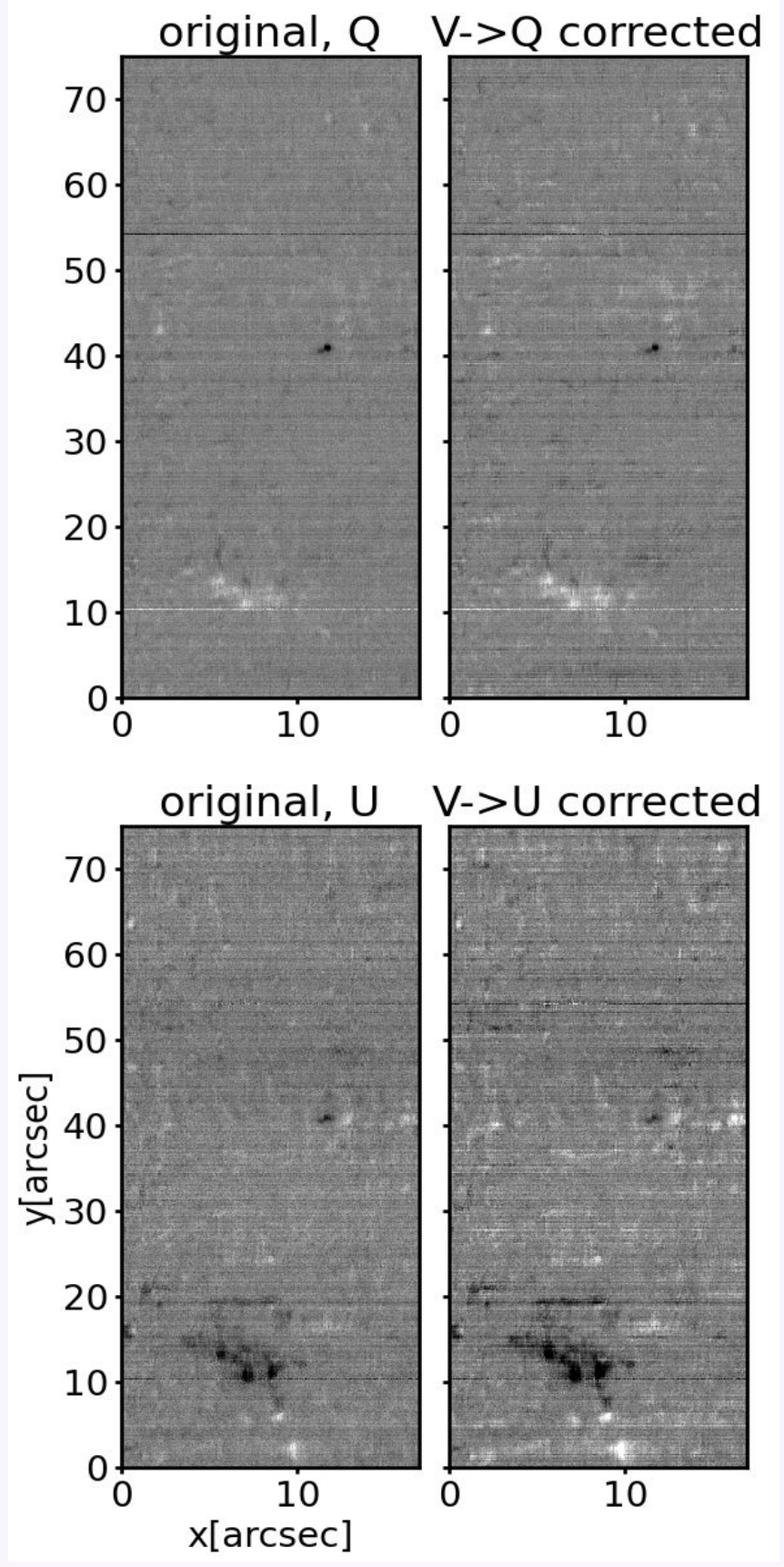
Step 2: Compensate for cross-talk V-> Q,U

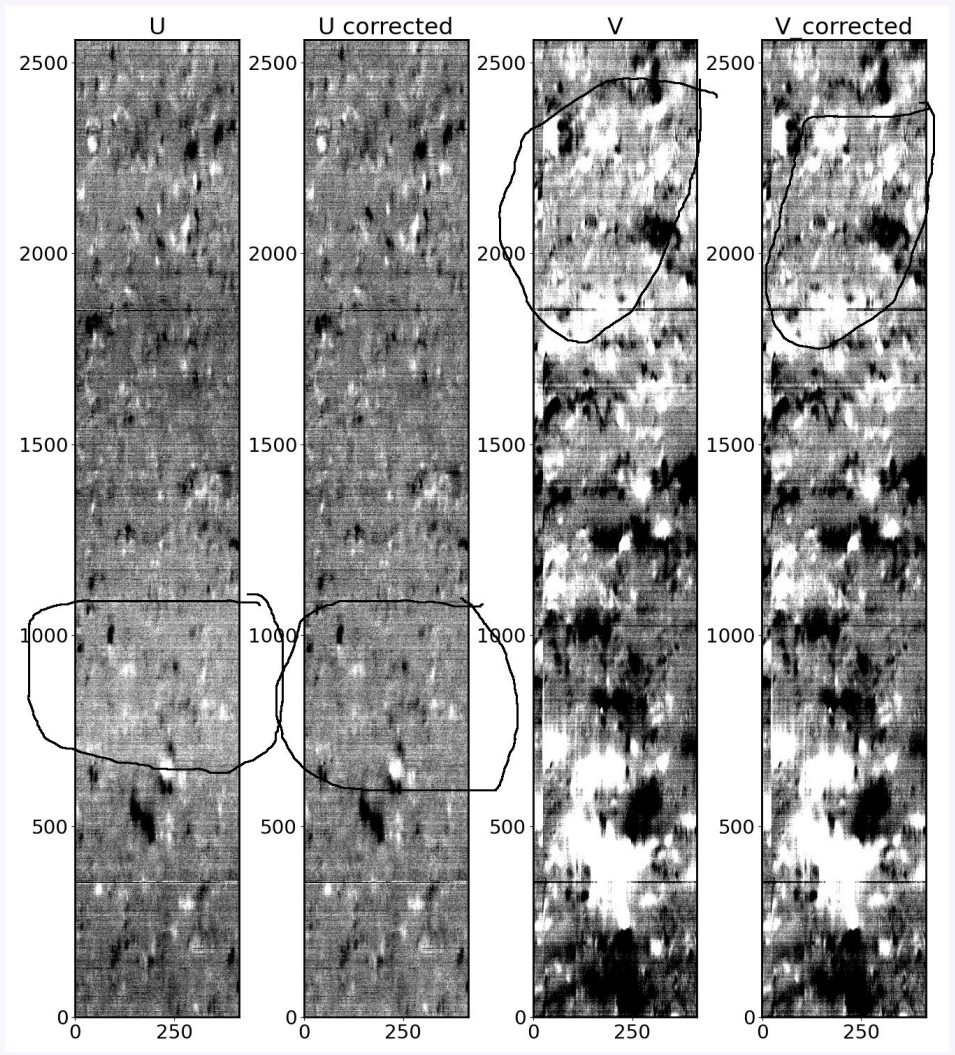
The cross-talk β from Stokes-V was estimated under the assumption that V>> Q~U~0. and that asymmetries produced by cross-talk are even or odd functions.

$$\beta_{V\to Q}=\frac{\int_\lambda Q(\lambda)*V(\lambda)\,d\lambda}{\int_\lambda V(\lambda)^2\,d\lambda} \qquad \beta_{V\to U}=\frac{\int_\lambda U(\lambda)*V(\lambda)\,d\lambda}{\int_\lambda V(\lambda)^2\,d\lambda}$$

$$Q_{corr2}=Q_{corr1}+\beta_{V\to Q}*V$$

$$U_{corr2}=U_{corr1}+\beta_{V\to U}*V$$





Step 3. Compensation for residual continuum polarization and fringe-patterns

Even after crosstalk calibration, there is still an offset from zero mean intensity at continuum wavelengths in Stokes Q, U, and V and a residual fringe-like pattern on the order of 1e-3. These residual patterns are compensated for by fitting the continuum intensity with a low order polynomial function.

Magnetic field estimate

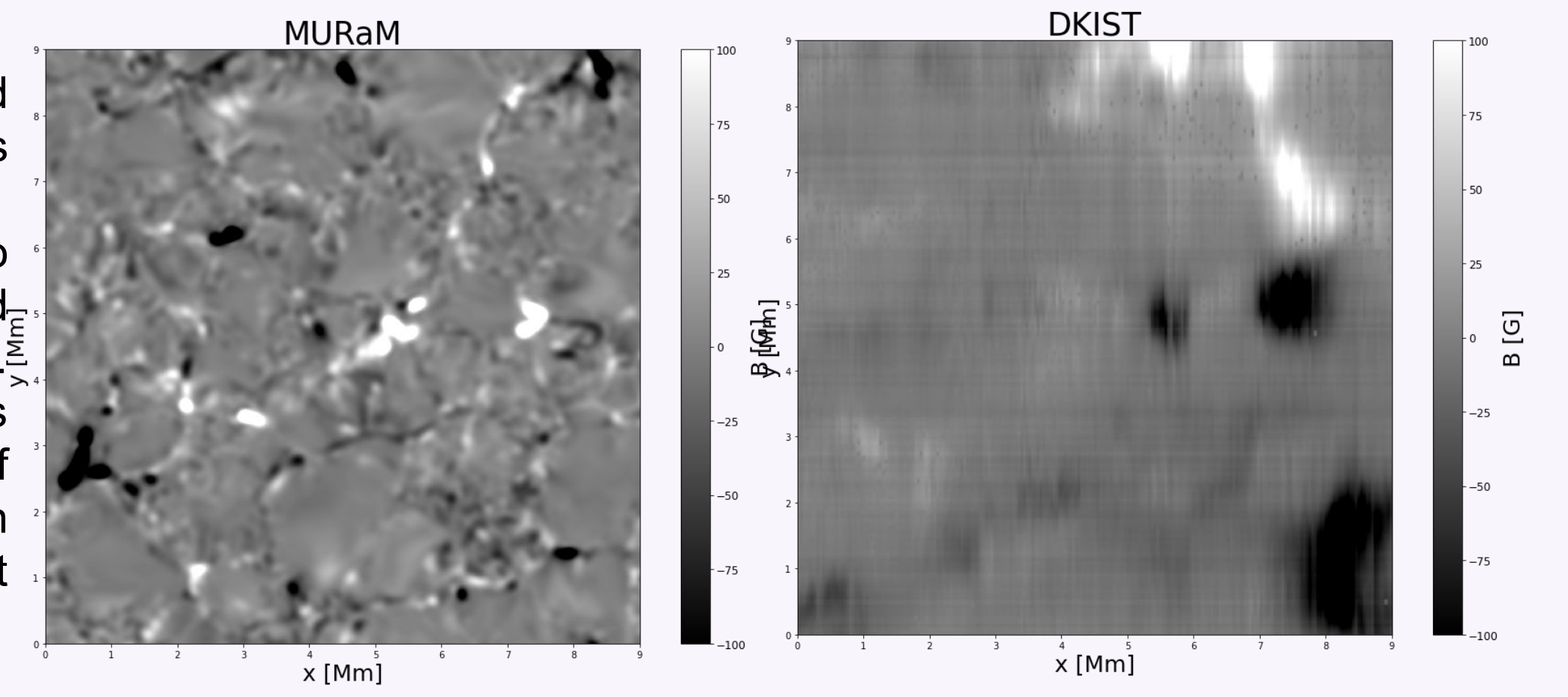
Properties of the magnetic field were estimated inverting the Fe I 630.1 and 630.2 nm lines simultaneously, under the assumption that physical and magnetic properties of plasma are invariant with height (Milne-Eddington approximation). To this end we employed the publicly available pyMilne code (de la Cruz Rodriguez 2019).

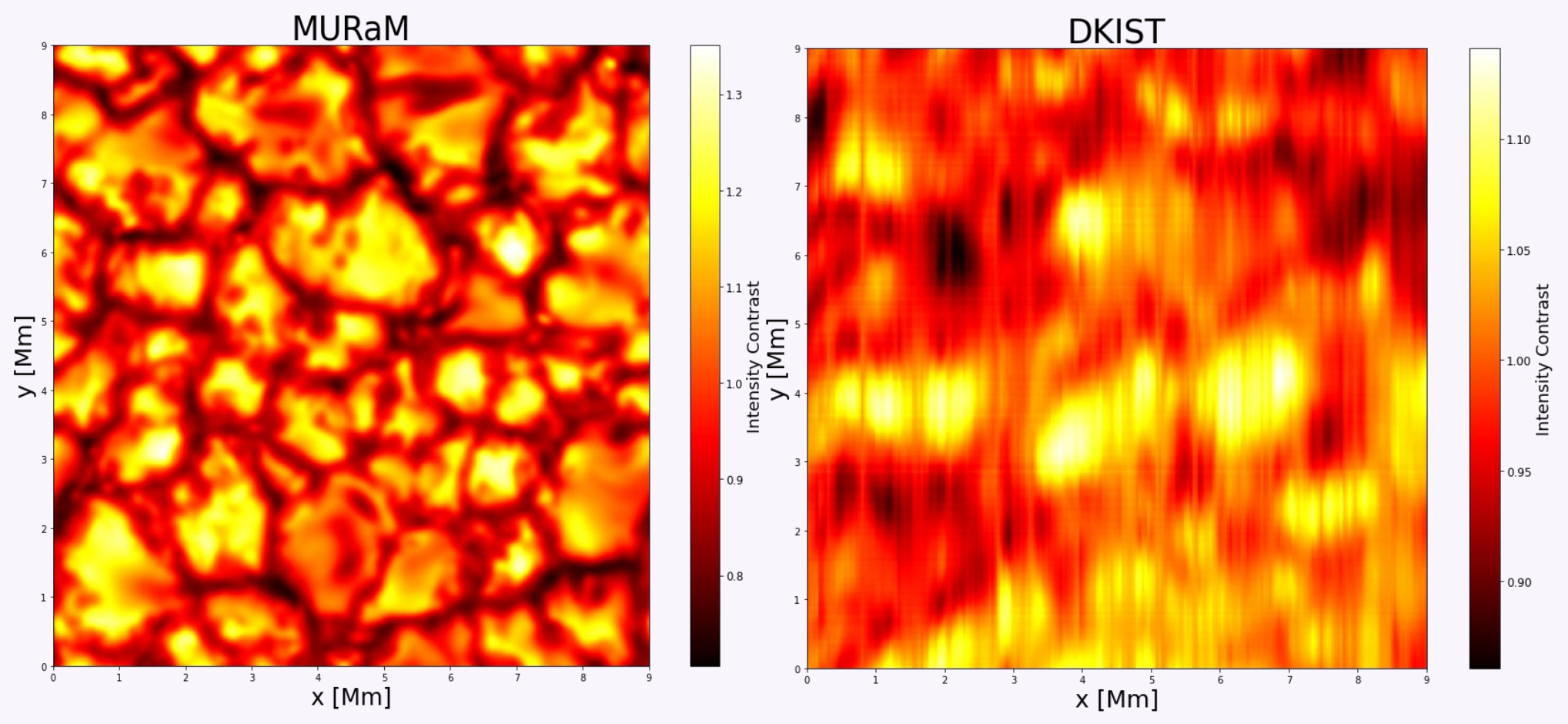
We are mostly interested in estimates of the magnetic field intensity along the line-of-sight B_{LOS}.

The B_{LOS} uncertainty in our measurements (estimated as the standard deviation of B_{LOS} in a very quiet area) is ~ **4 G.**

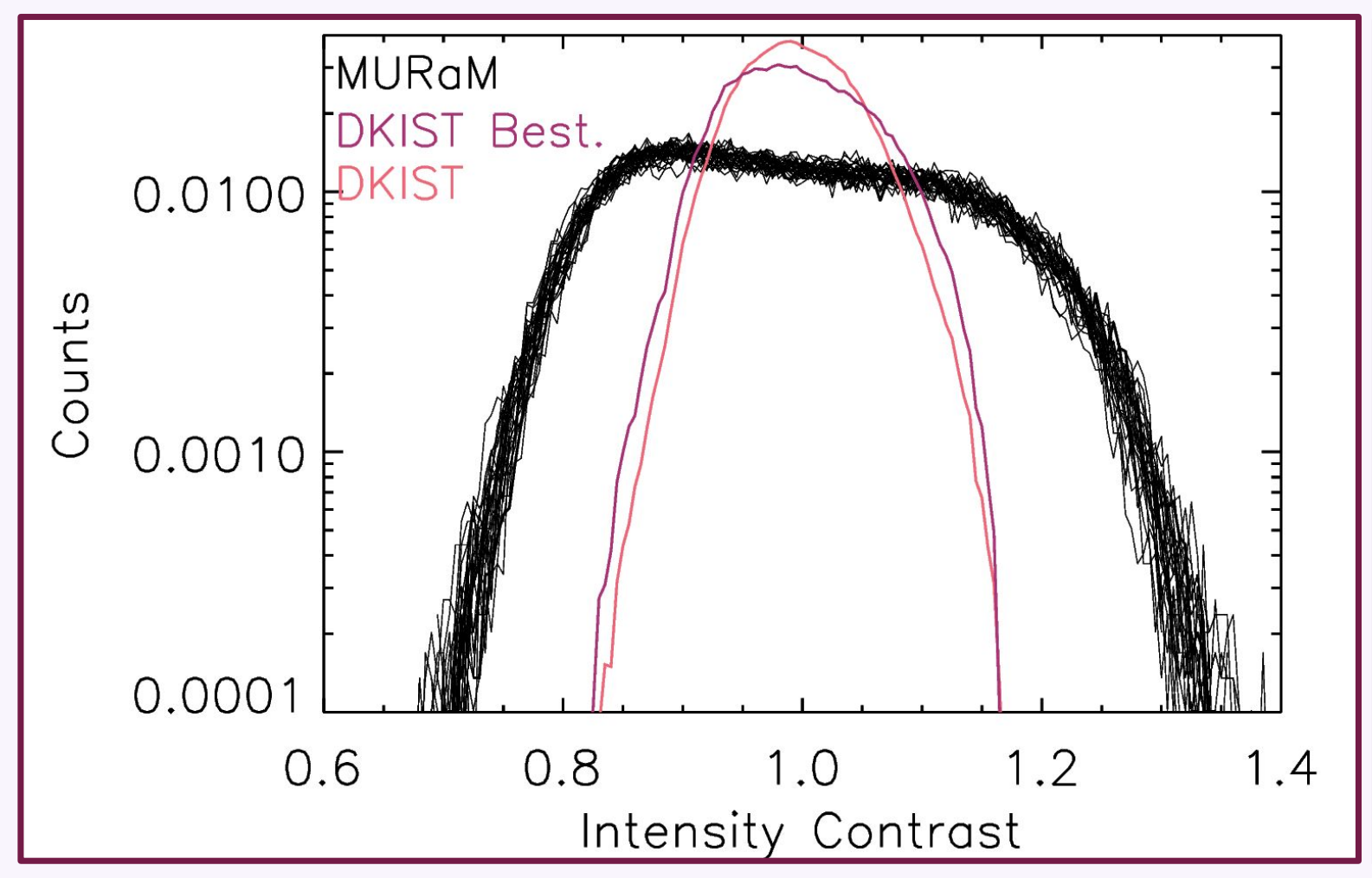
Results

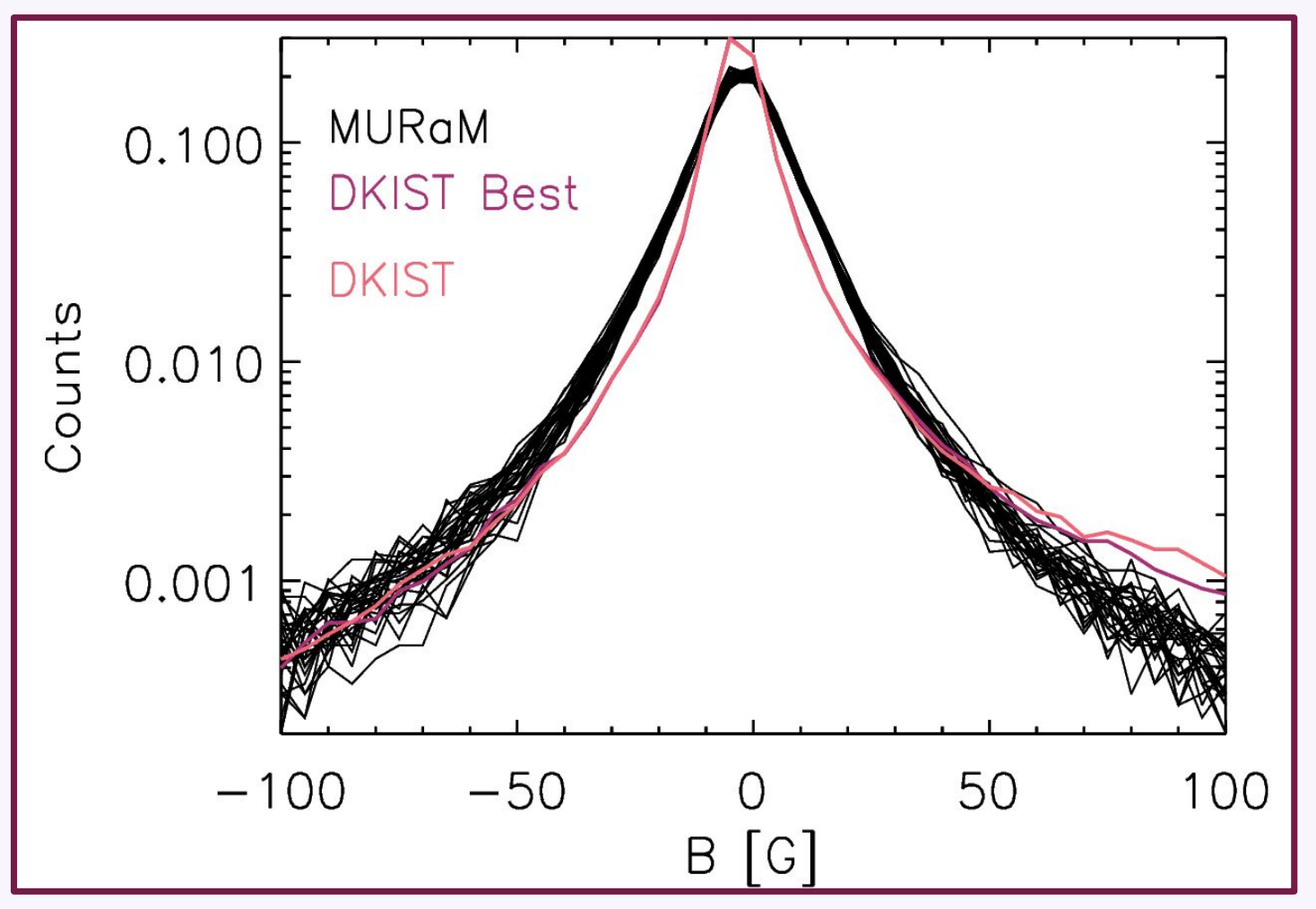
Comparison of magnetic field line-of-sight intensity maps (B_{LOS}) obtained applying Milne-Eddington inversions to a MURaM snapshot (left), and DKIST observations (right). The DKIST field-of-view was cropped to match the field of view of the simulations. In both images the B_{LOS} is saturated at +/- 100 G.





Comparison of maps of Intensity contrast (Intensity normalized to the average Intensity in the field-of-view) at 630 nm continuum obtained with MURaM snapshot (left), and DKIST observations (right).

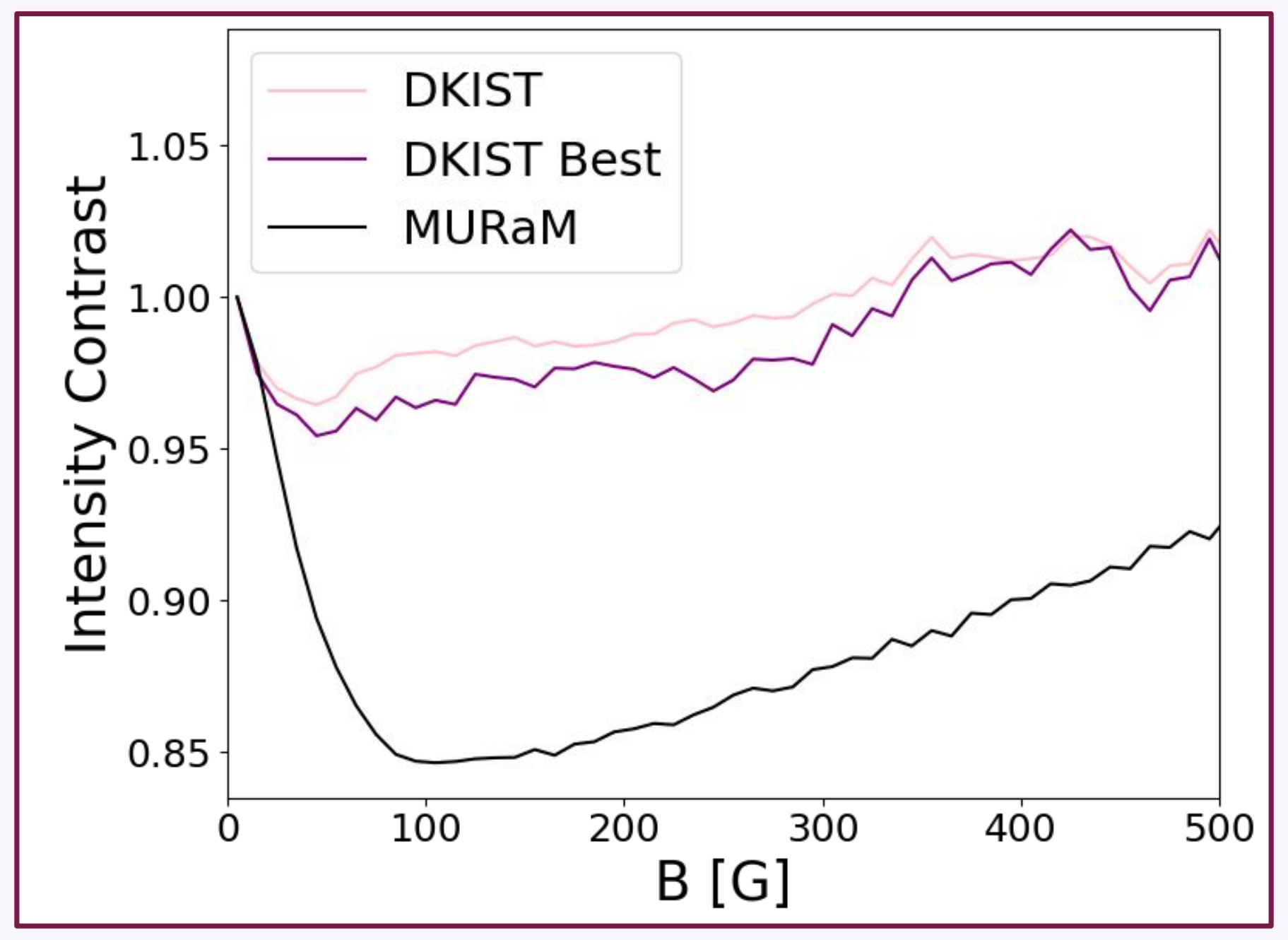




The Intensity contrast and the B_{LOS} distributions are compared in the top-left and top-right plots, respectively. The narrower distributions in the observations indicate that the spatial resolution of the DKIST observations is below the diffraction limit of the telescope.

	<|B|> [G]	<B> [G]	B_rms [G]	I_rms
MURaM	12	0.02	33	12%
DKIST	16	6.5	48	5.2%
DKIST Best.	16.4	6.5	48	6%

Table on the top compares the average properties of the magnetic field and of the intensity at 630 nm continuum obtained from MURaM and DKIST observations. The average signs and un-signed B_{LOS} agree within uncertainties, but the Intensity rms contrast is 55% lower in observations, indicating that ViSP spatial resolution is lower than the diffraction limit. Bottom row show results obtained for slit positions where I_{rms} is larger than the average I_{rms} . If we exclude the network patch at (8",12") the signed and un-signed fluxes are 7 G and 0.8 G, respectively, while the I_{rms} value does not change significantly.



Plot on the top shows that the I vs B_{LOS} curve presents the typical 'fish-hook' shape reported in the literature (Schnerr and Spruit 2011). The lower contrast and the lower B_{LOS} value of the position of minimum of the curve found in observations (~65 G) with respect to simulations (~100 G), are compatible even in this case with the fact that ViSP observations are not diffraction limited. The I vs B_{LOS} relation is indeed similar to the relation obtained with HINODE/SOT observations (Schnerr and Spruit 2011).

Conclusions

We performed a preliminary analysis of DKIST observations acquired on July 7, 2022 during DKIST Commissioning phase 1. We present here results obtained from ViSP observations at the FeI 630.1/630.2 nm spectral range.

We found that the level 1 data provided by the DKIST data center are affected by residual cross-talk I-> U,V,Q and V-> Q,U, residual polarization in the continuum and low-frequency patterns (fringes) in the spatial domain. All these effects were compensated for in our data.

Comparison of observations with MURaM simulations degraded to the diffraction-limit of DKIST, indicate that the spatial resolution of ViSP data is lower than the diffraction-limit of the telescope. This is to be expected as typically diffraction limit is achieved by applying post-processing techniques.

The intensity vs B_{LOS} relation is compatible with results previously obtained from HINO/SOT observations.

We plan to continue the analysis by estimating the unresolved brightness using the method proposed by Schnerr and Spruit 2011. We will the exploit the unique DKIST multiwavelength capabilities to extend the analysis to the ViSP observations in the UV and IR, and to the VBI blue continuum.