Looking for Changes in Photospheric Temperature Gradients over Solar Cycle 24/25 Using Hinode/SP

James Crowley [1,2], Ivan Milic [3], Kevin Reardon [2], Gianna Cauzzi [2]
[1] University of Colorado, Boulder; [2] National Solar Observatory, Boulder; [3] Astronomical Observatory, Belgrade
james.crowley (at) colorado.edu

Motivation

Physical variations in the quiet solar photosphere throughout the solar cycle might be caused by subtle changes in the convective flows due to differing of magnetic fields. Previous studies have proposed the presence of other such systematic changes, for example, related to the size of the granular cells (Ballot et al., 2021). **By combining the high resolution of Hinode/SP with the Spectropolarimetric Inversions Based on Response Functions (SIR) code, we are able to infer physical conditions of the lower solar photosphere.**

SIR Inversions

SIR is an inversion code which infers the height stratification of atmospheric parameters from observed Stokes profiles. We invert quiet Sun Hinode SOT/SP maps over the cycle and analyze the distributions of thermodynamic parameters (temperature, temperature gradient, line–of-sight velocity). We analyze quantity gradients between log(τ) = 0 and -2, where the 6301/6302 spectral lines are most sensitive. The chosen complexity (e.g. number of nodes) of the inversion affects the retrieved parameters (Fig 1), requiring a careful selection of the inversion configuration.

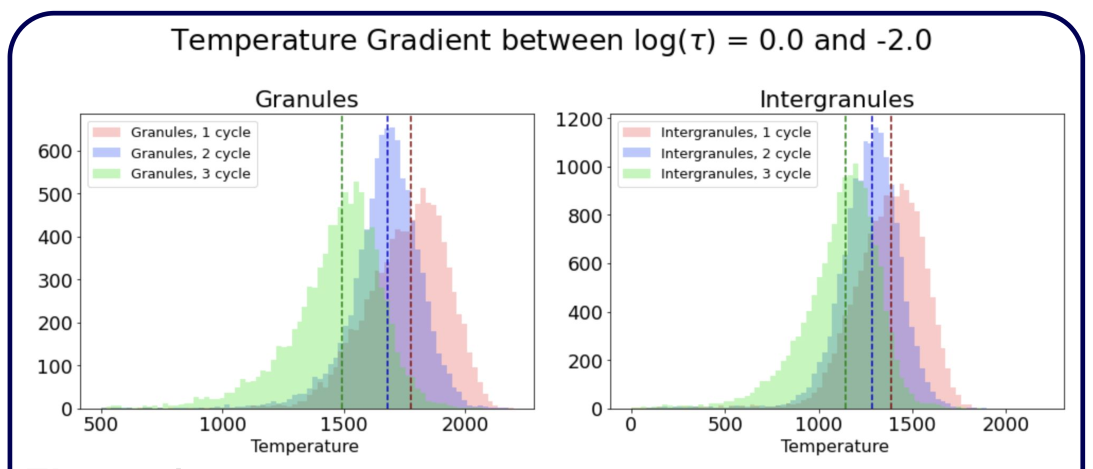

Figure 1: An inversion scheme with more cycles and nodes (increasing from red→blue→green) results in a reduction of the temperature gradient of hundreds of Kelvin.

Inversion strategy:

- We invert only the 6301 Å line, to avoid systematics because of differing atomic parameters and magnetic sensitivity.
- We settled on 5 temperature nodes, as it is the configuration which gives best fits without overfitting the spectra.
- After inversion, we spatially filter the data, and re-invert to increase spatial coherency.
- Magnetic pixels are not used for the analysis.
- All remaining pixels are clustered in 3 groups via K-means clustering: granules, intergranules and "in-between". Only granules and intergranules are used for the analysis.

Data Selection

Carefully choosing datasets ensures that changes are due to the solar cycle, and not observational effects. The following requirements were used selecting data:

1. **At or very near the disk center:** this is to minimize projection or limb effects.
2. **Quiet Sun:** we chose datasets without obvious magnetic signatures like sunspots.

Based on these requirements, 7 datasets were selected and inverted: two from 2008 (Cycle 24 minimum), three from 2014 (Cycle 24 maximum), and two from 2020 (Cycle 25 minimum).

Inversion Results

Across years, inverted parameters agree extremely well: in intergranules, parameters differed by less than 1%, and by a significantly larger amount of up to 4% in granules.

This is seen in both temperature gradients and line-of-sight velocities: these parameters are relatively independent (i.e. not degenerate), so this implies that there could be larger changes in granules then in intergranules throughout the solar cycle, but further analysis is required.

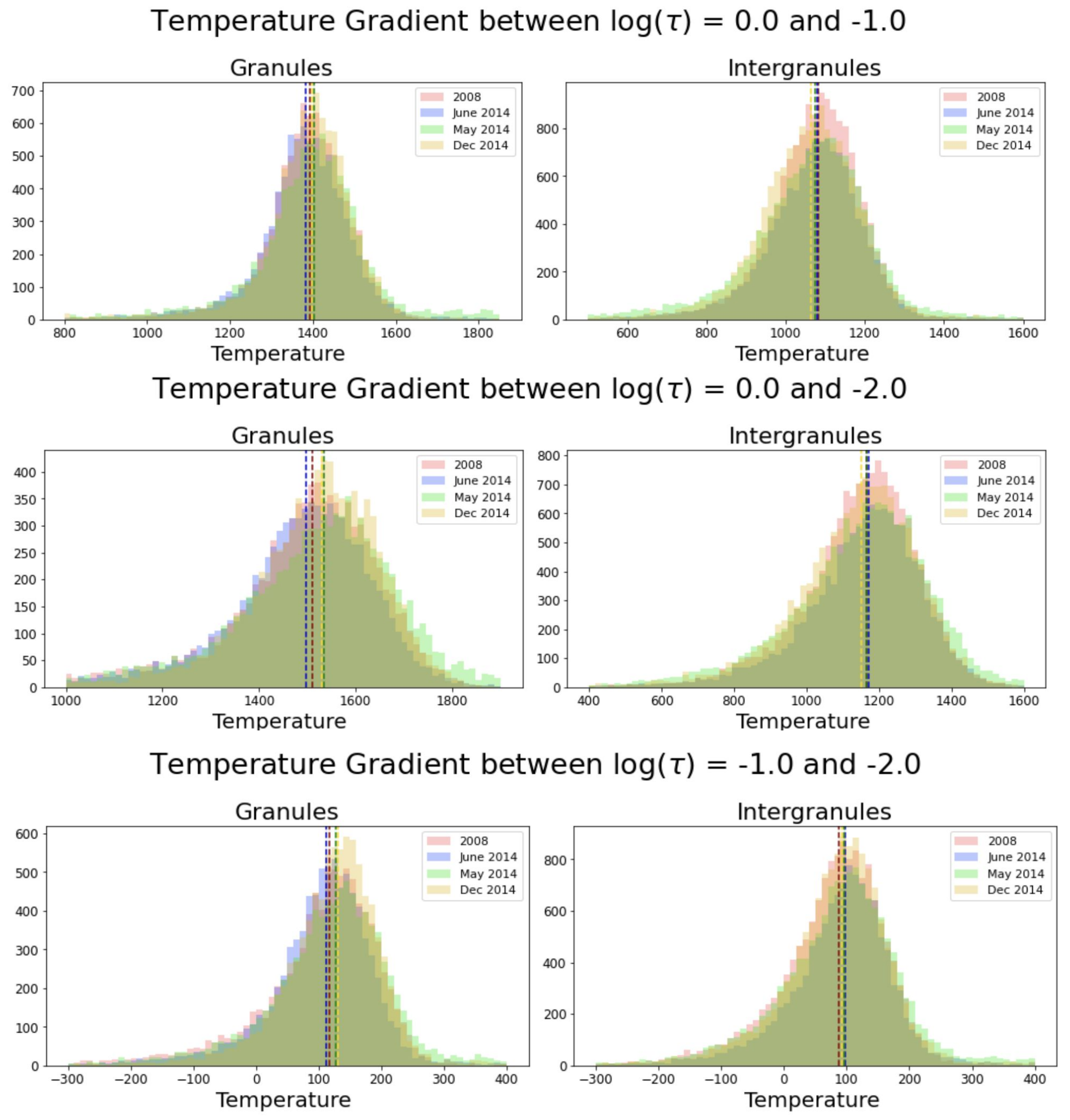

Figure 2: The resulting inverted temperature gradient at different optical depths in granules (left) and intergranules (right) for 4 selected datasets, plotted on top of each other.

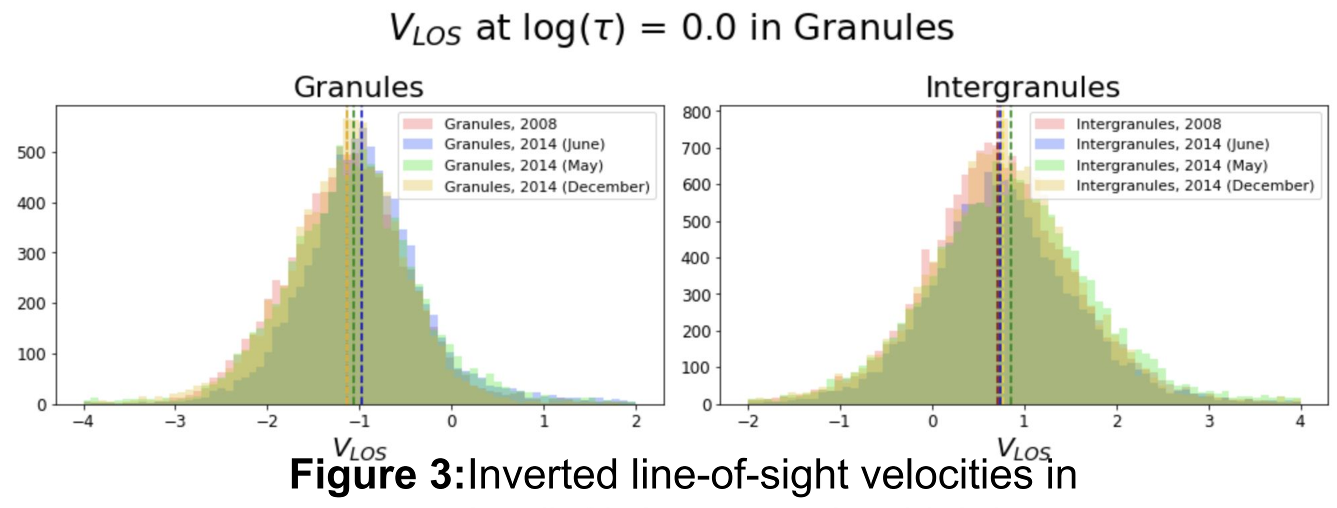

Figure 3: Inverted line-of-sight velocities in granules (left), intergranules (right)

Notable Findings

Not all the selected sets have the same spatial binning or exposure time - still, the inversion outputs agree remarkably well (Fig. 4). That the inferred parameters do not vary for different observation configurations is a surprising result!

For example: Why do two fields with different binning (and thus resolution) still yield similar atmospheric distributions?

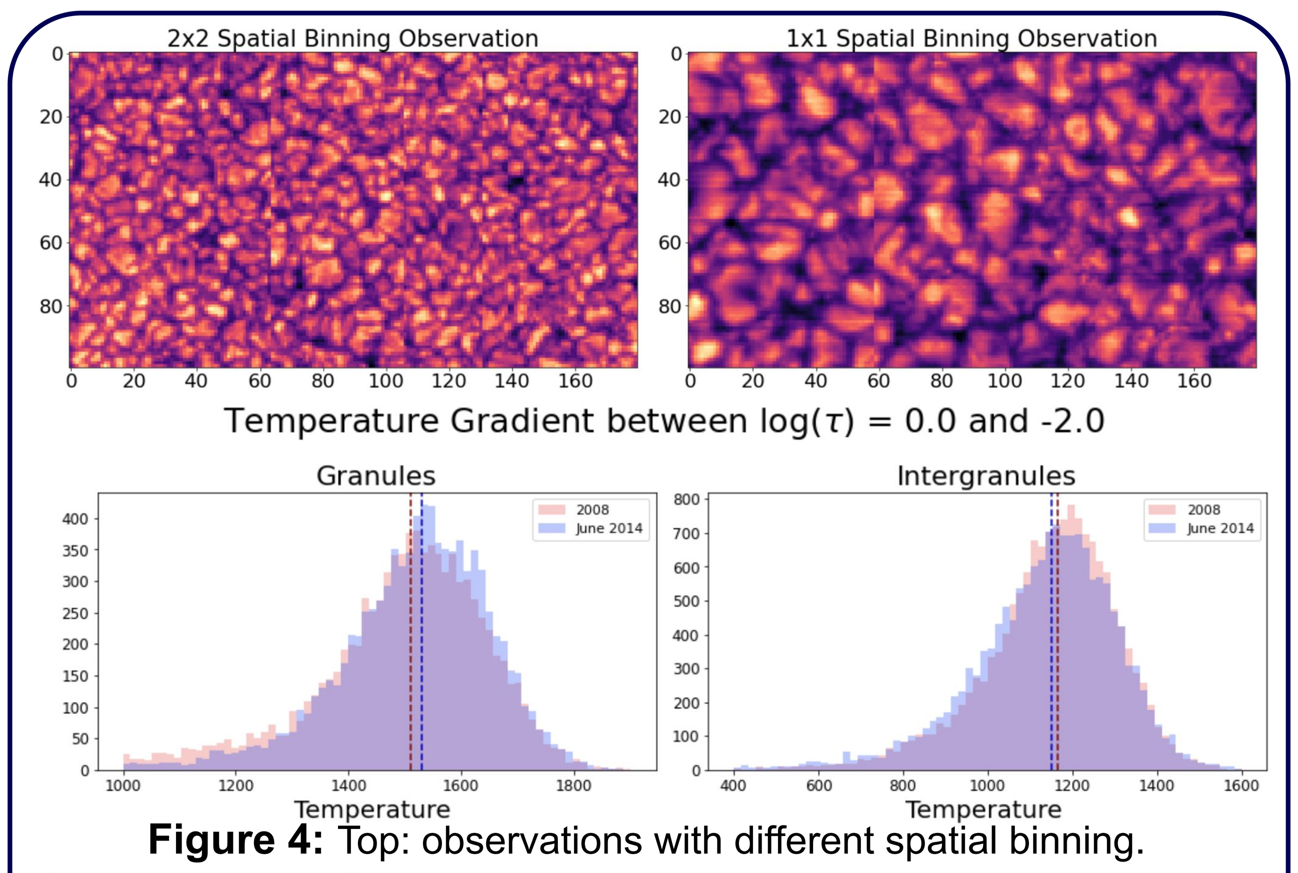

Figure 4: Top: observations with different spatial binning. Bottom: Inverted Temperature gradients in granules and intergranules of the two datasets, showing strong agreement.

Conclusions

Parameters retrieved from throughout the solar cycle have generally been stable over time, but there appear to be some cycle-dependent differences in the temperature gradients in granules. Inversion of more datasets and further analysis will clarify whether this is real effect or a result of systematic bias.

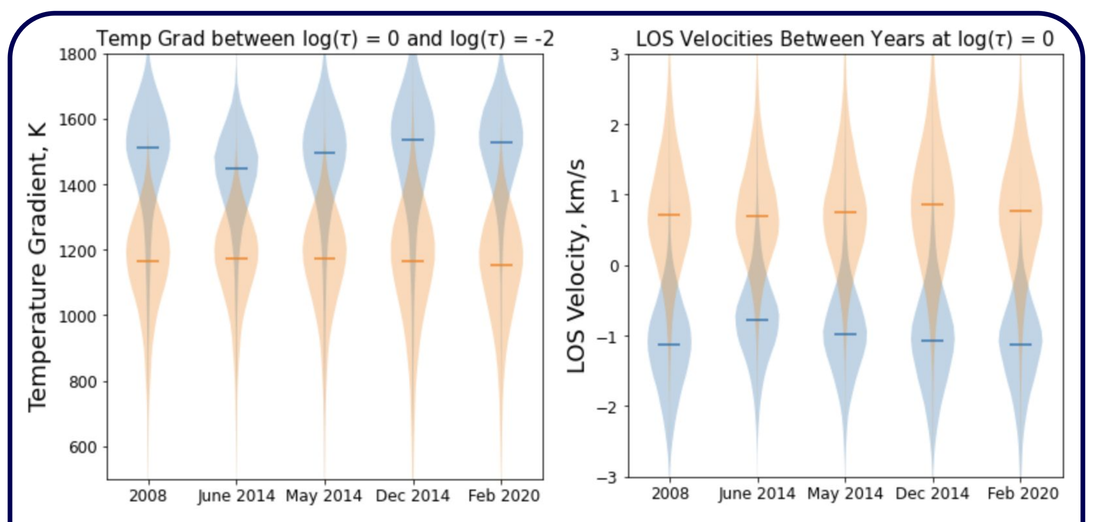

Figure 7: Summary of inverted parameters. Blue: Granules, Orange, Intergranules

Future Work

1. One dataset from June 2014 shows a statistically significant differences in granules: **the median temperature gradient decreases by 7%.** This could be because this observation has lower contrast; this is supported by the fact that independently inverted quantities, like the line-of-sight velocity, still agree strongly with other datasets. The lower contrast could be due to the target being off disk-center, or maybe the SP focus was not optimized. We will attempt to eliminate such systematic effects by re-doing the analysis on data from the Hinode irradiance program (**HOP 0079**).
2. Next, inverting more datasets from solar cycle 24 and 25 will help form a better picture of how parameters might be changing throughout the solar cycle.

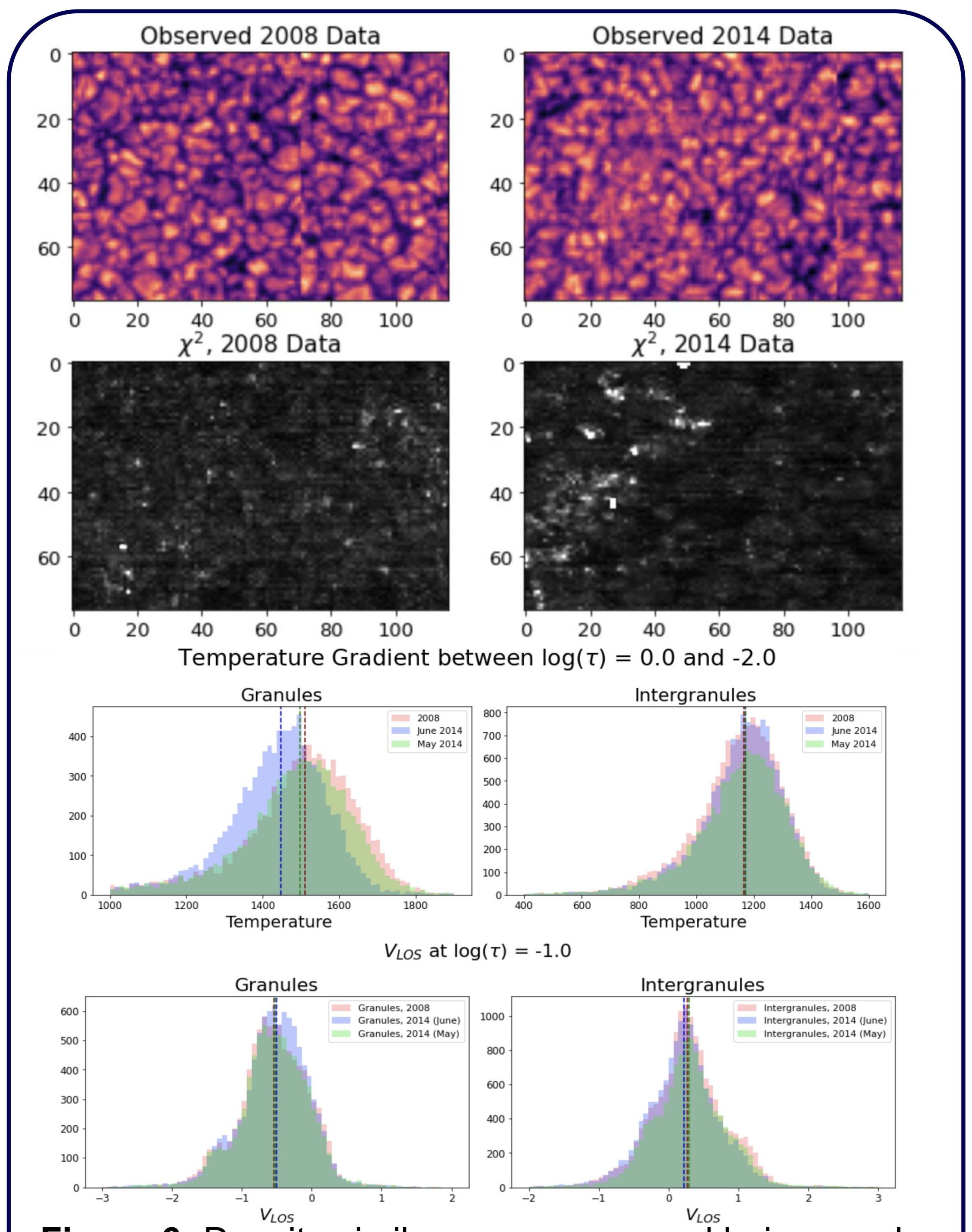

Figure 6: Despite similar appearance and being nearly equally-well fit (top rows), the inverted temperature gradient in the granules for the June 2014 dataset differs by 7% from the other datasets (top left histogram). LOS-Velocities (bottom histograms), however, agree well.

References

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