analysis of sample MDM all-sky camera FITS files

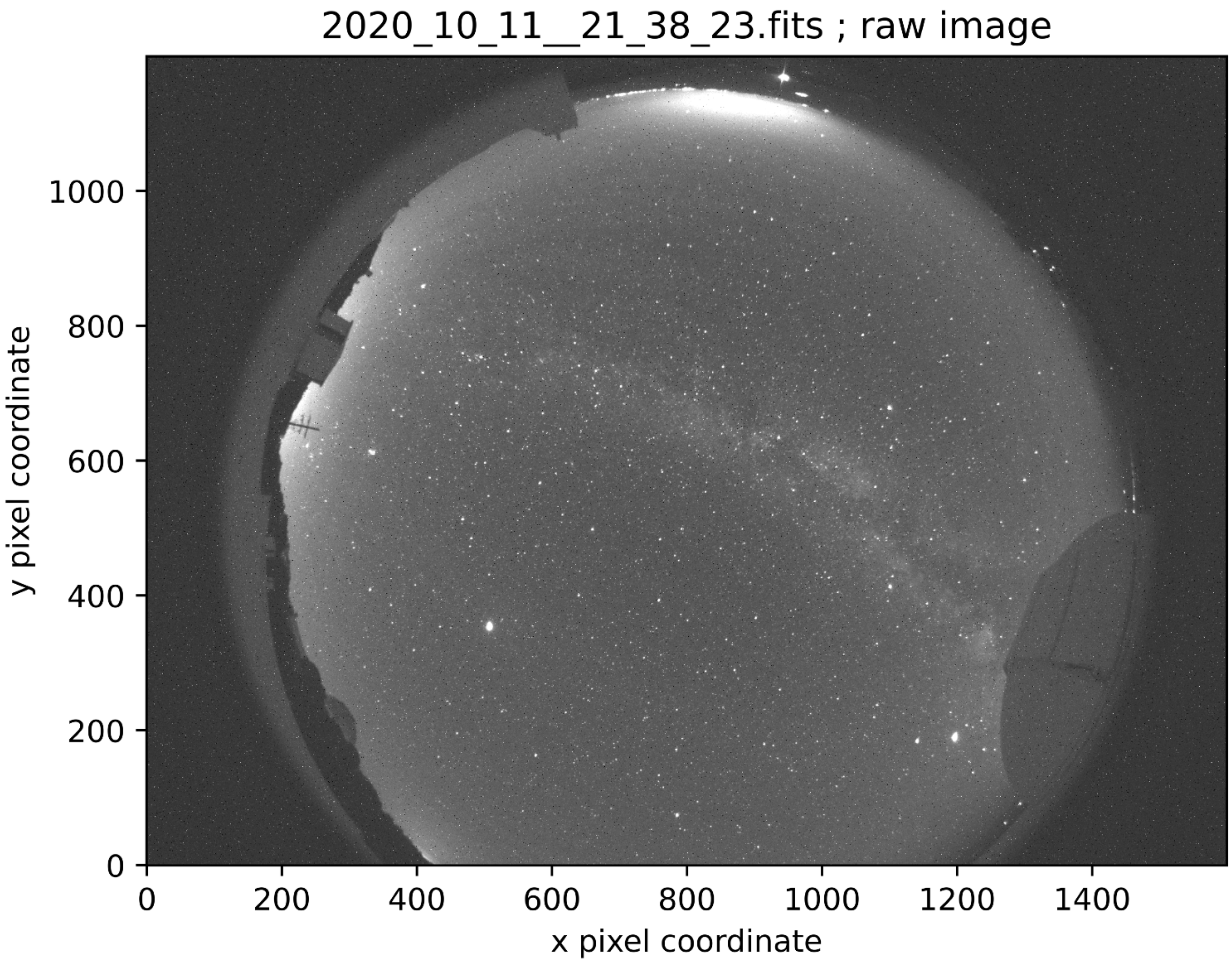
FITS images provided by Eric Galayda (MDM/Michigan)

Analysis by Aaron Meisner, Dick Joyce, Arjun Dey

background information

- MDM Observatory is located on Kitt Peak and operates an OMEA all-sky camera:
  - http://mdm.kpno.noao.edu/Allsky.html
  - The MDM all-sky camera model is OMEA-2.0M-HMA
- In routine/standard operations, MDM only provides its all-sky camera images in JPG format
- The MDM all-sky camera is capable of providing FITS image readouts
  - On the night of 2020 October 11-12 Eric Galayda (MDM/Michigan) specially read out six MDM all-sky camera exposures as FITS files and provided them to Dick Joyce
- The purpose of these sample MDM FITS readouts is to investigate the potential for mapping sky brightness and transparency across the sky using an OMEA all-sky camera system

example image



- The MDM all-sky camera images are 1600 pixels by 1200 pixels
- The pixel sidelength is ~8.6 arcminutes
- A portion of the sky with Alt < 18, 140 < Az < 215 not available

table of sample images

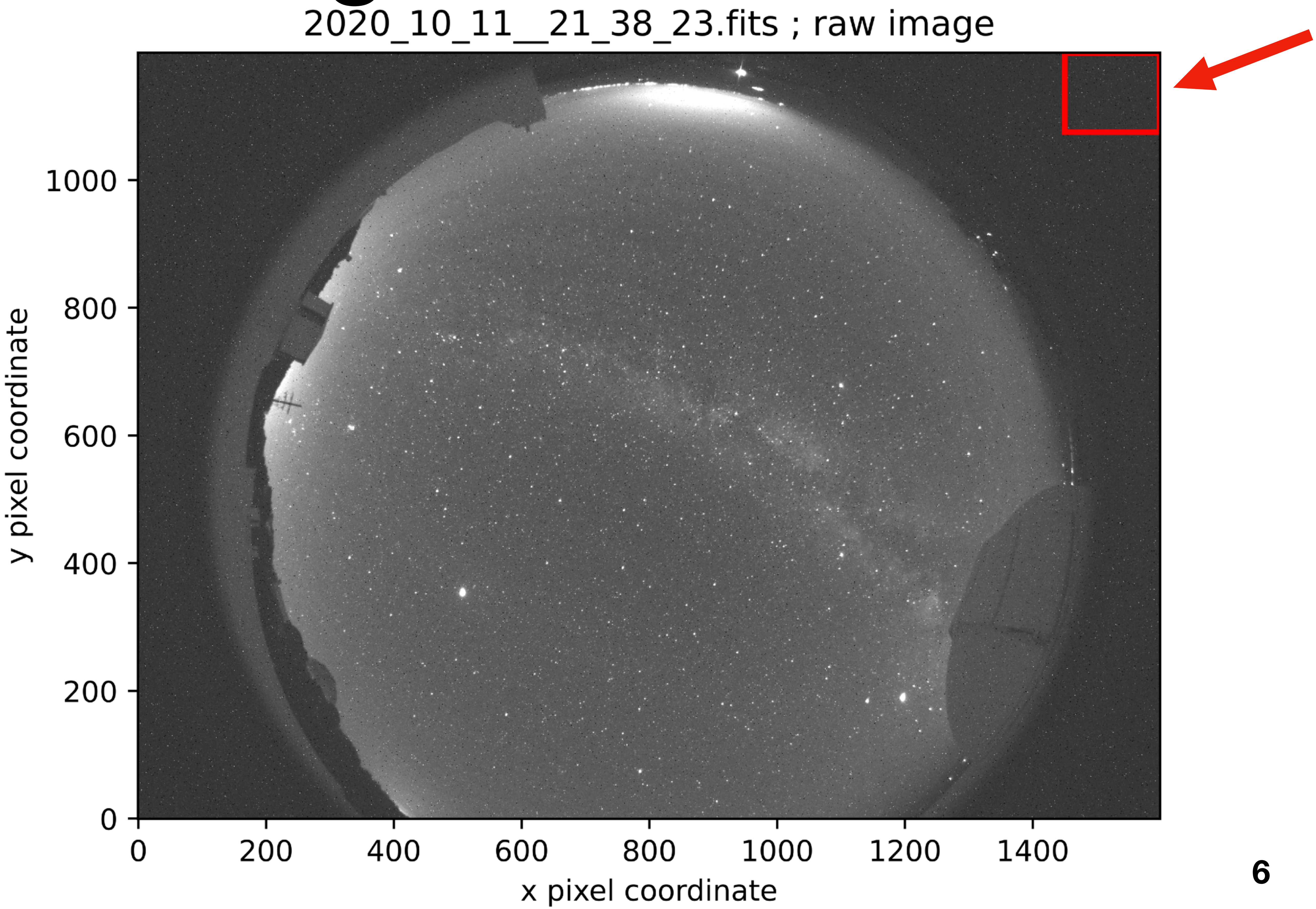
filename	KPNO local date/time	Moon up?
2020_10_11__21_38_23.fits	2020-10-11 21:37:14.72	no
2020_10_11__22_16_18.fits	2020-10-11 22:15:09.56	no
2020_10_11__23_17_30.fits	2020-10-11 23:16:21.45	no
2020_10_12__00_13_48.fits	2020-10-12 00:12:39.80	no
2020_10_12__02_30_55.fits	2020-10-12 02:29:46.69	yes
2020_10_12__05_17_12.fits	2020-10-12 05:16:03.74	yes

- Exposure time is 50 seconds in all cases

detrending

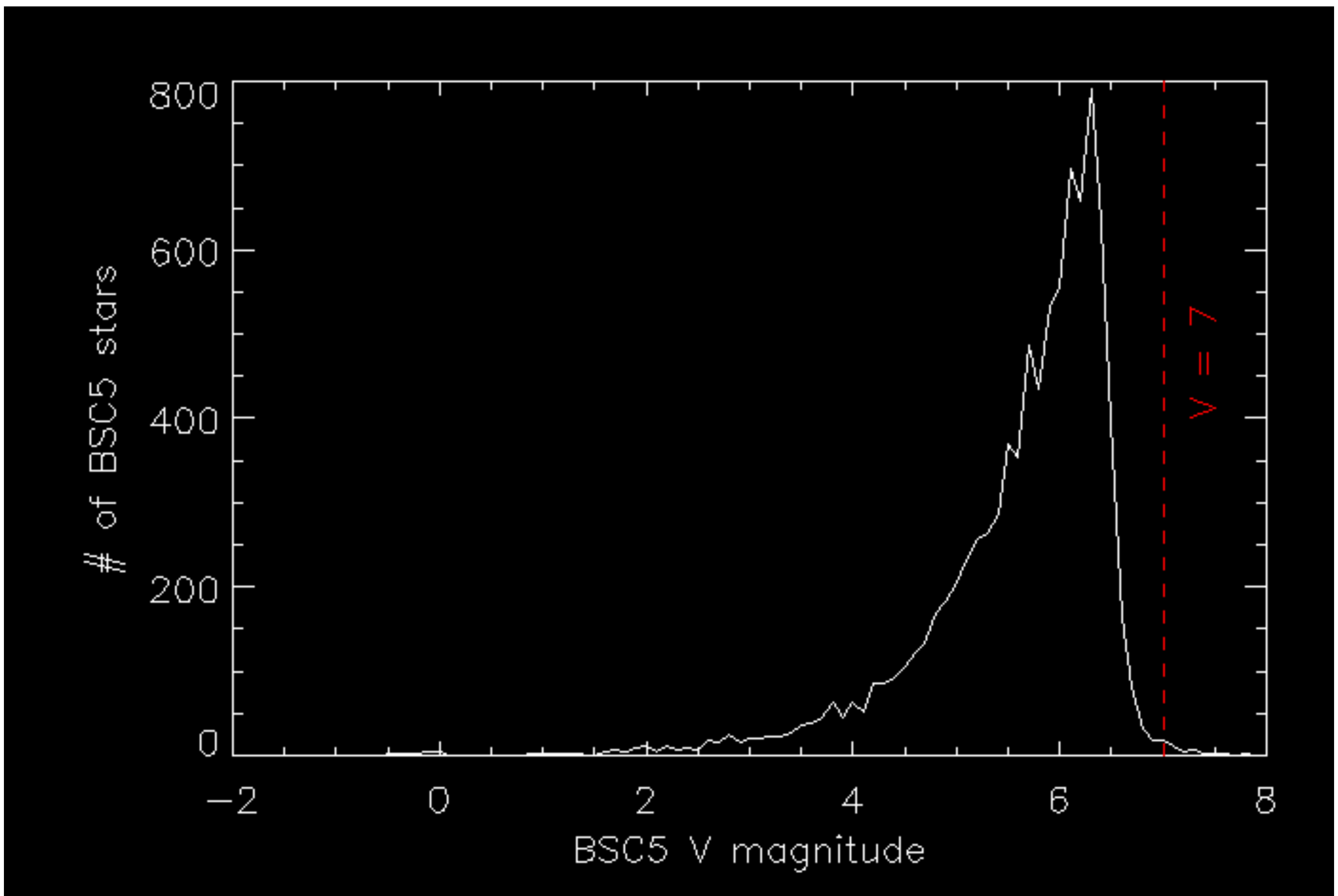
- Build a bad pixel mask by taking the median of the six FITS images, then flagging pixels that are unusually high/low relative to a 3x3 pixel median
    - 1.2% of pixels are flagged as bad
- Interpolate over these hot/cold pixels in the raw data before doing any astrometry/photometry
- Use part of the non-illuminated area of each exposure to determine the (dark+bias) background level
    - This is useful for estimating the sky counts

“off region” for bias+dark



bright star catalog

- http://tdc-www.harvard.edu/catalogs/bsc5.html
- BSC5 V mags are quantized at 0.1 mag intervals
- The BSC website says BSC5 “is more or less complete to V=7”, but it appears to cut off brighter than that



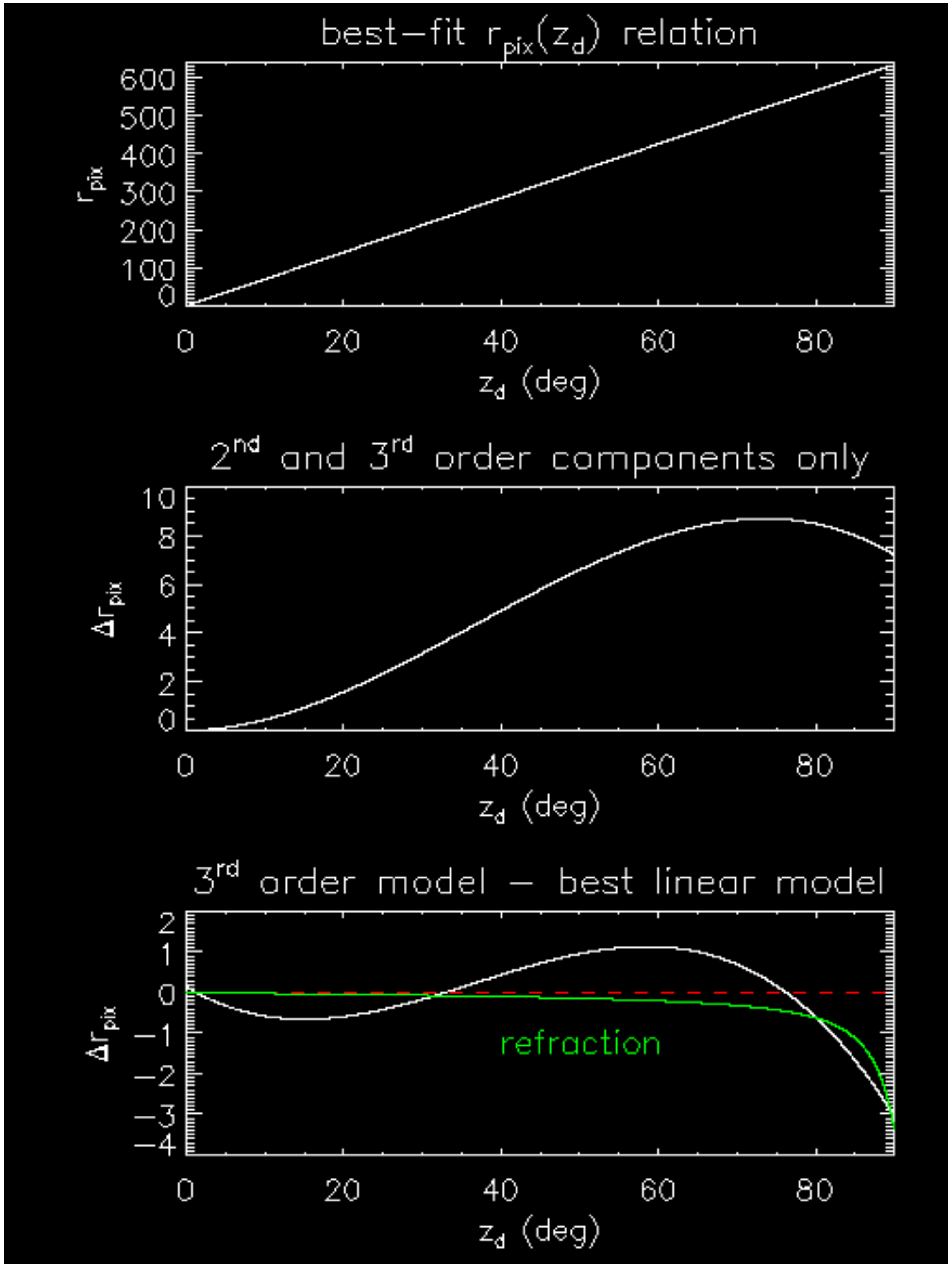
astrometric model

- The astrometric model maps from (Alt, Az) to pixel (x, y) so that bright stars can be identified and subsequently have their centroids refined on a per-exposure basis

- To create the model, I jointly fit for the position angle of N relative to +y, the zenith x pixel coordinate, the zenith y pixel coordinate, and a third order polynomial that translates between zenith distance in degrees and radius from zenith in units of pixels

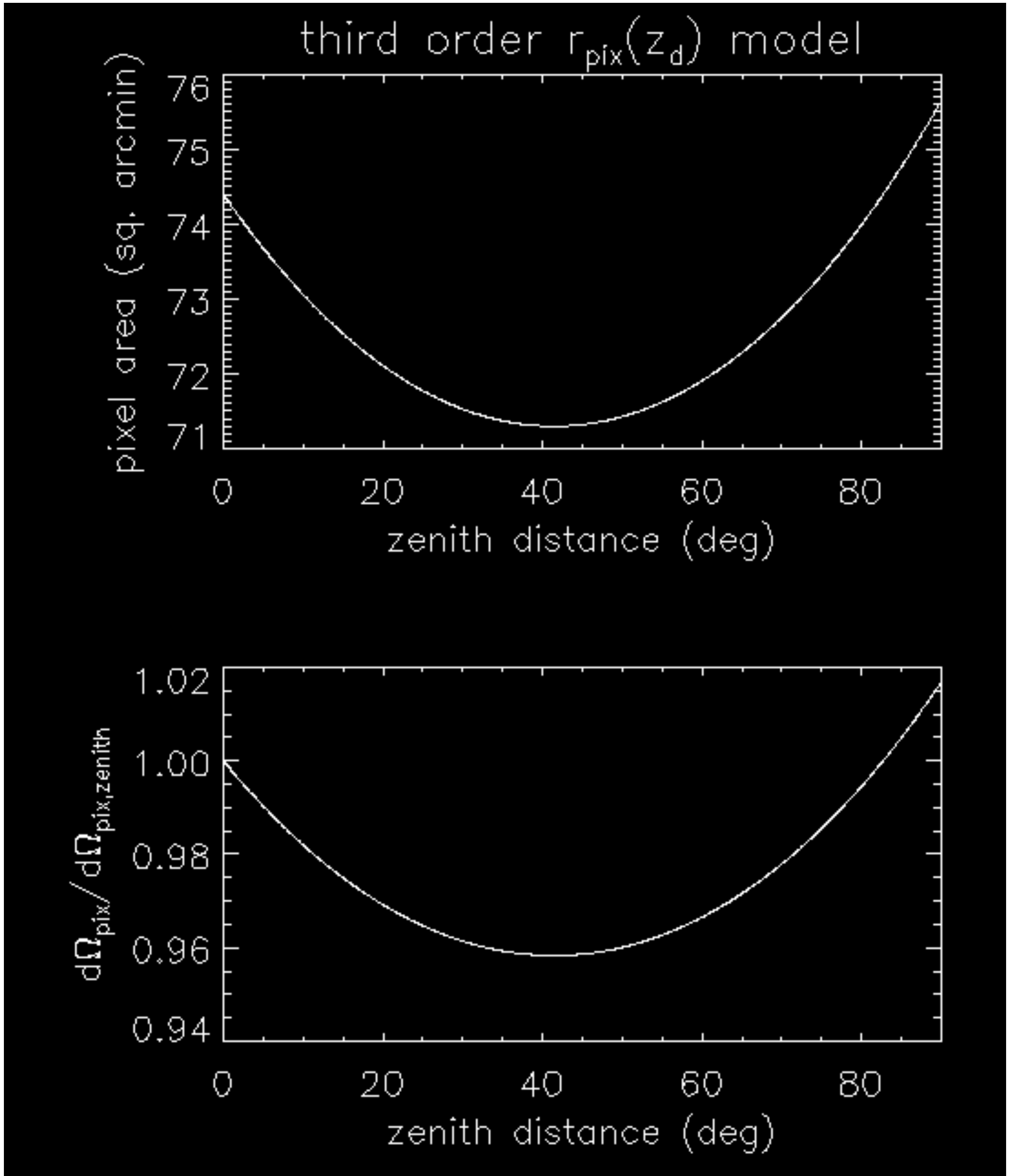
  - This model was fit using the measured pixel coordinates of ~75 V <= 3 stars

astrometric model



- The plots at left show the results of the astrometric model fit.
- The radius from zenith is quite linear with zenith distance.
- The non-linear part of the mapping from zenith distance to radius appears to be soaking up the imprint of refraction on apparent zenith distance.
- If I were to re-do this analysis, I would work in terms of apparent zenith distance rather than actual zenith distance so that refraction is incorporated into the model.
- The best-fit model has a 2D RMS of 1.05 pixels = 0.15 degrees.

variation of pixel solid angle

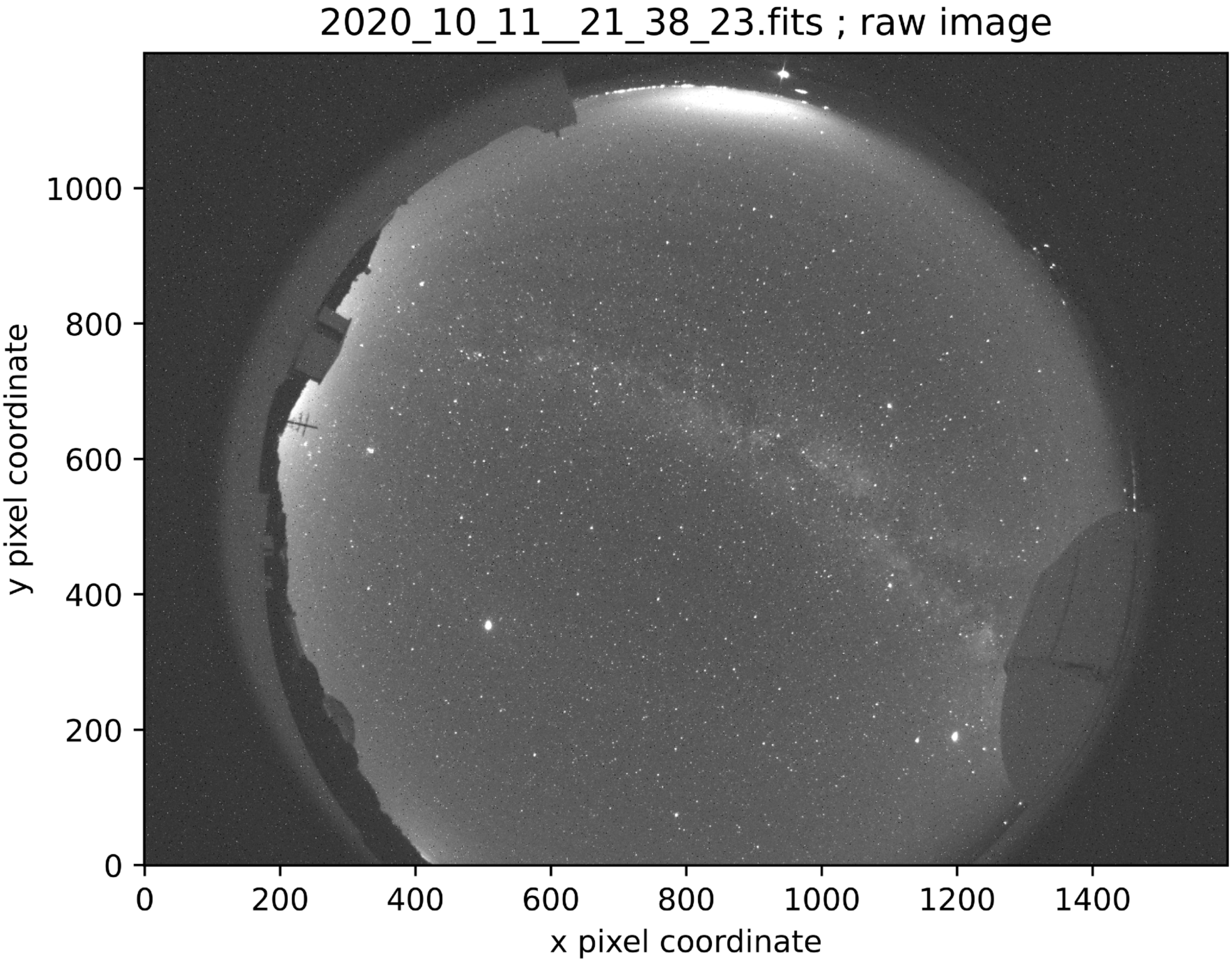


- The variation of pixel solid angle implied by the best-fit astrometric model is not especially huge, ~6% peak-to-peak.
- This suggests that variation of the pixel solid angle shouldn't have a large effect on the aperture photometry provided that the aperture used is reasonably large.

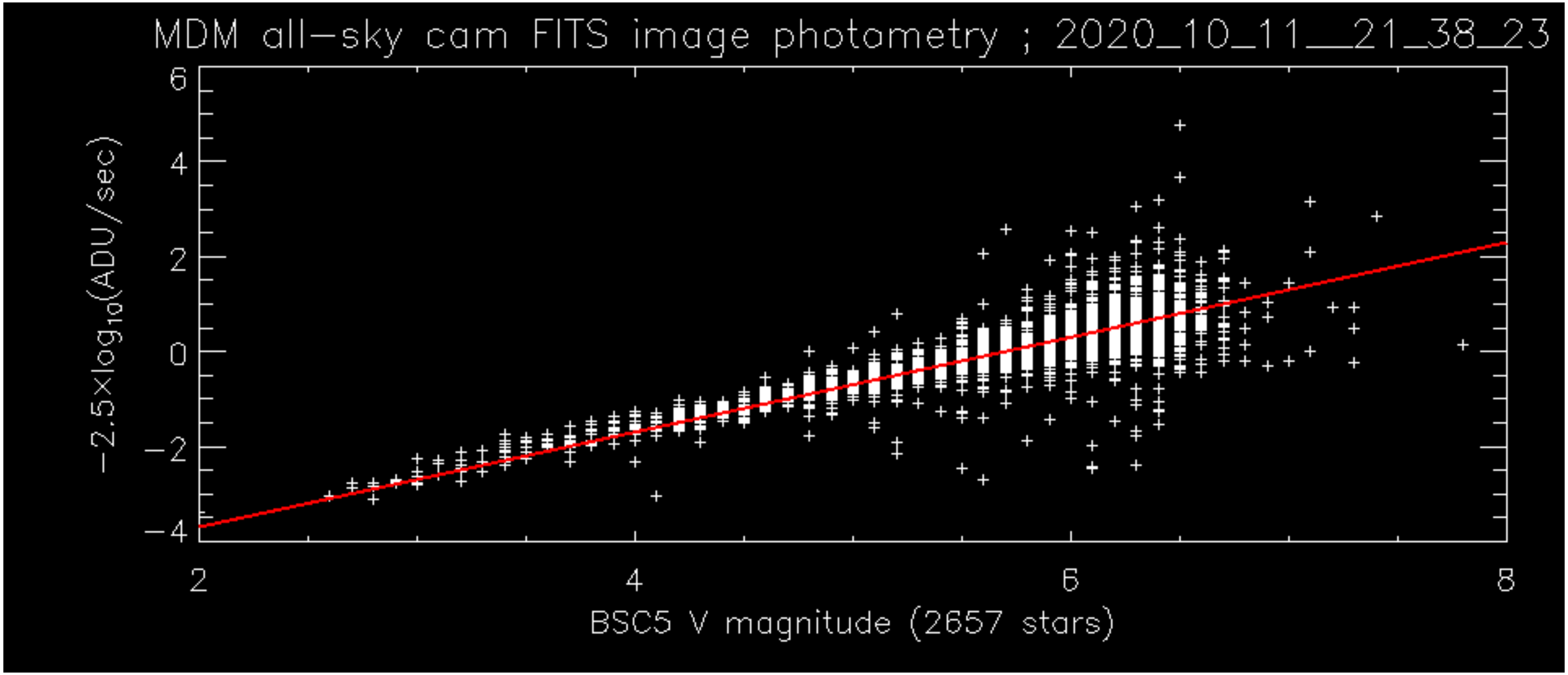
centroid refinement and photometry

- Use astrometric model to predict all BSC5 (x, y) pixel coordinate centroids
- Use iterative flux-weighted centroiding to refine these initial guesses for each star in each exposure
- Perform aperture photometry
- Attempt to reject saturated sources by removing cases with a peak (raw image) value of 240 ADU or larger

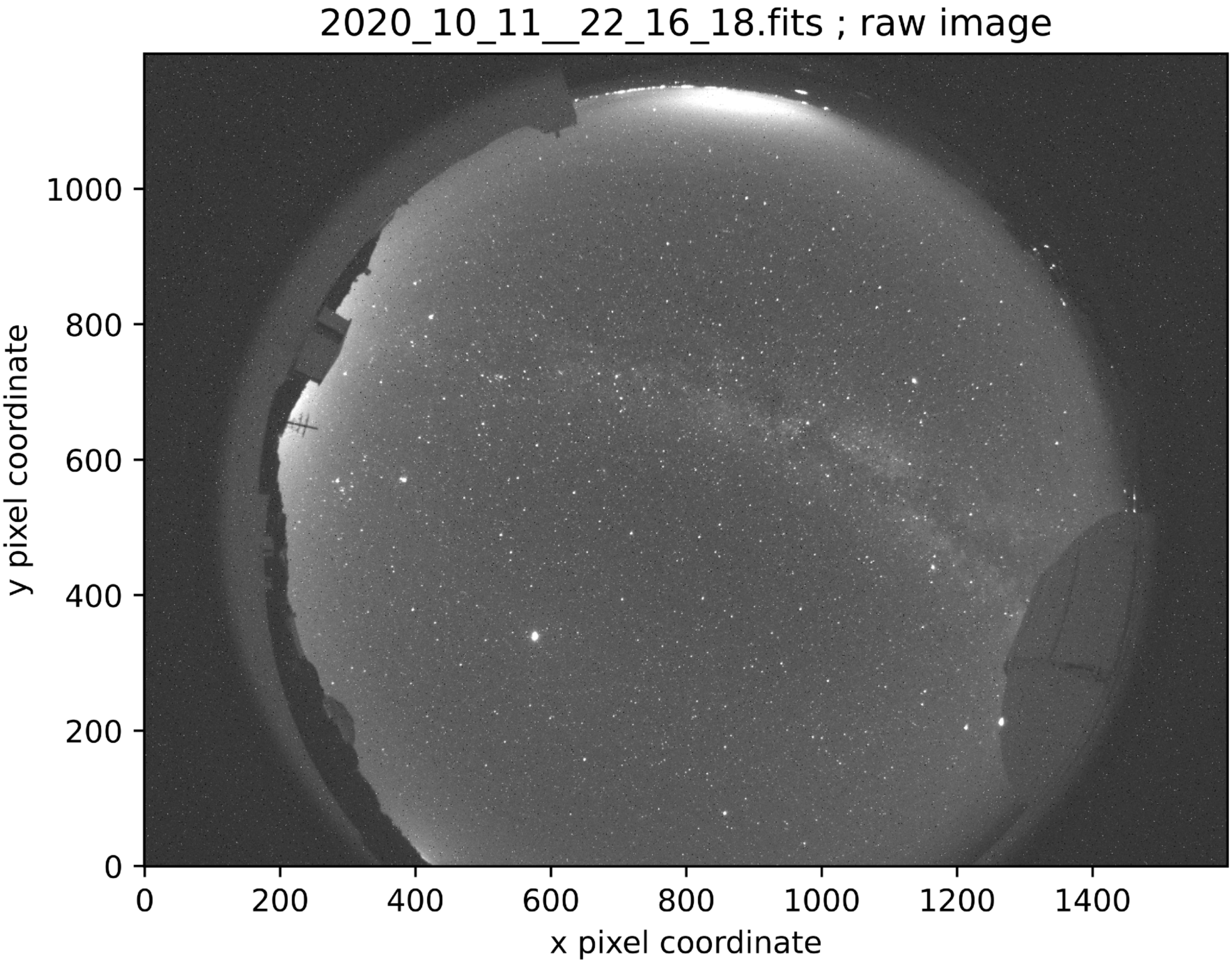
Photometry: 1st image



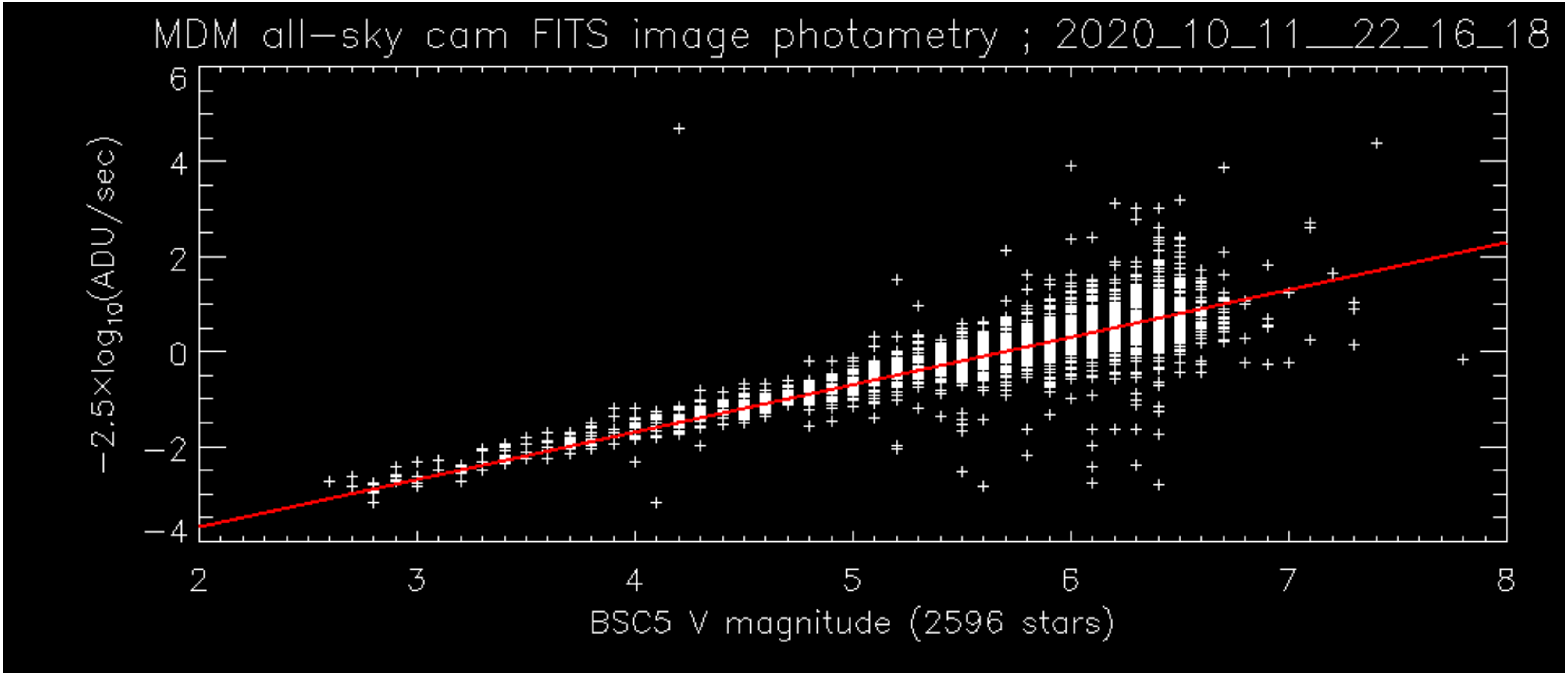
Photometry: 1st image



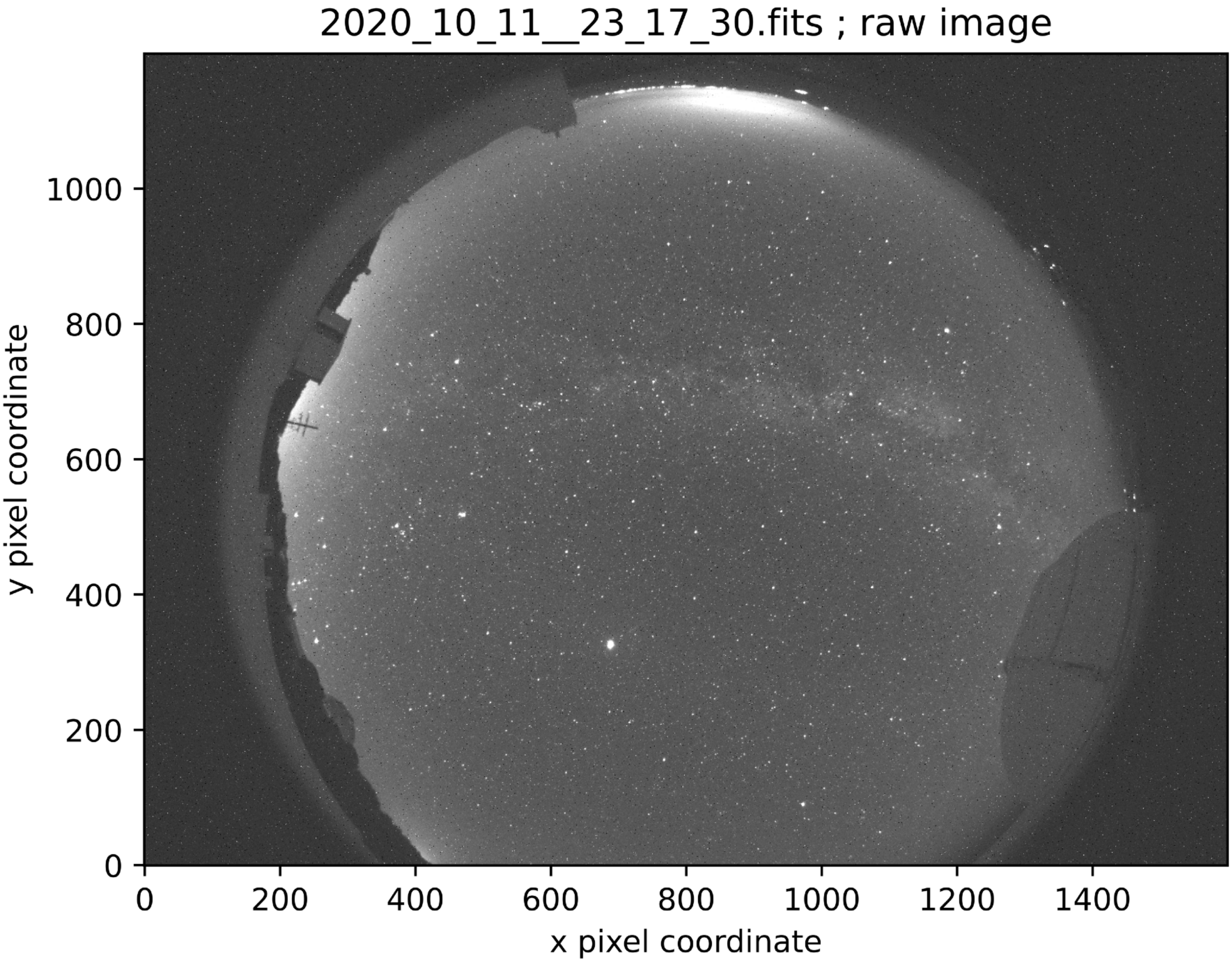
Photometry: 2nd image



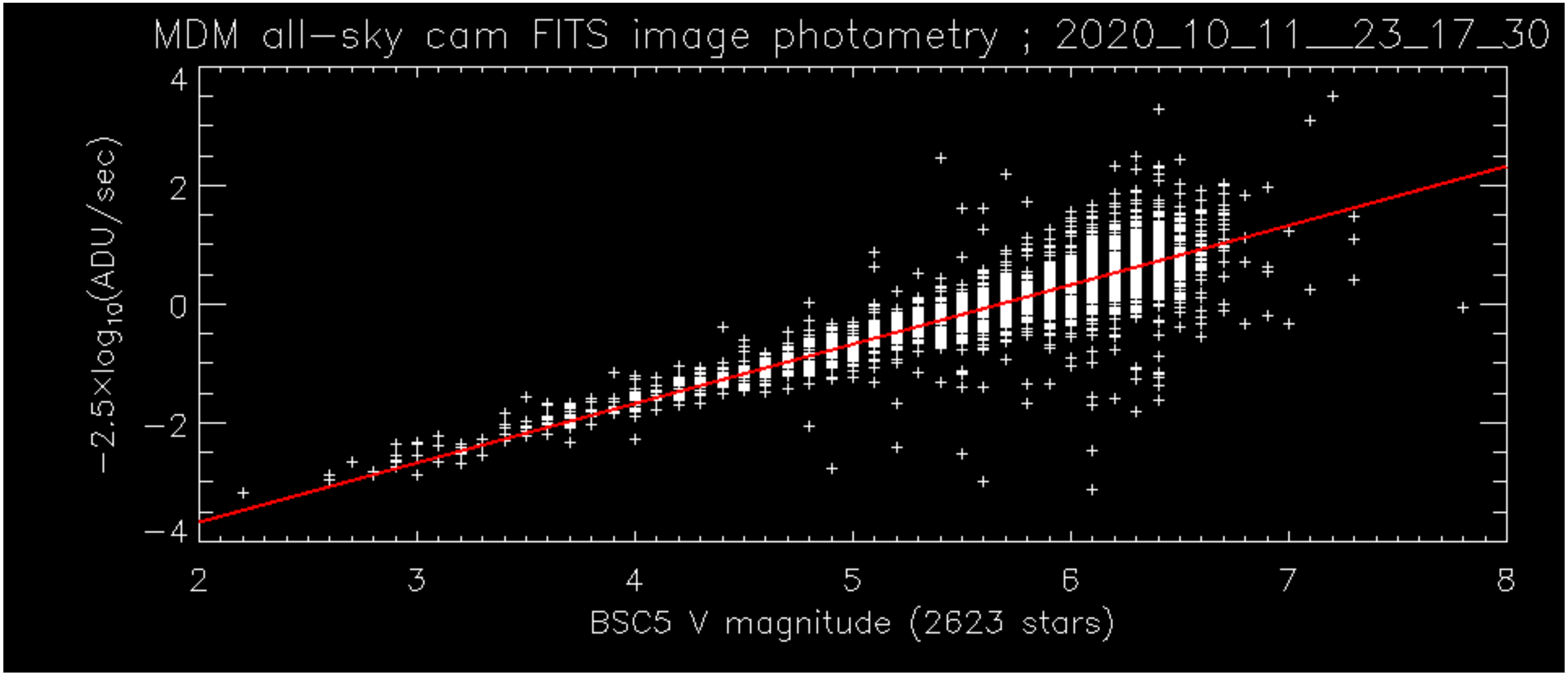
Photometry: 2nd image



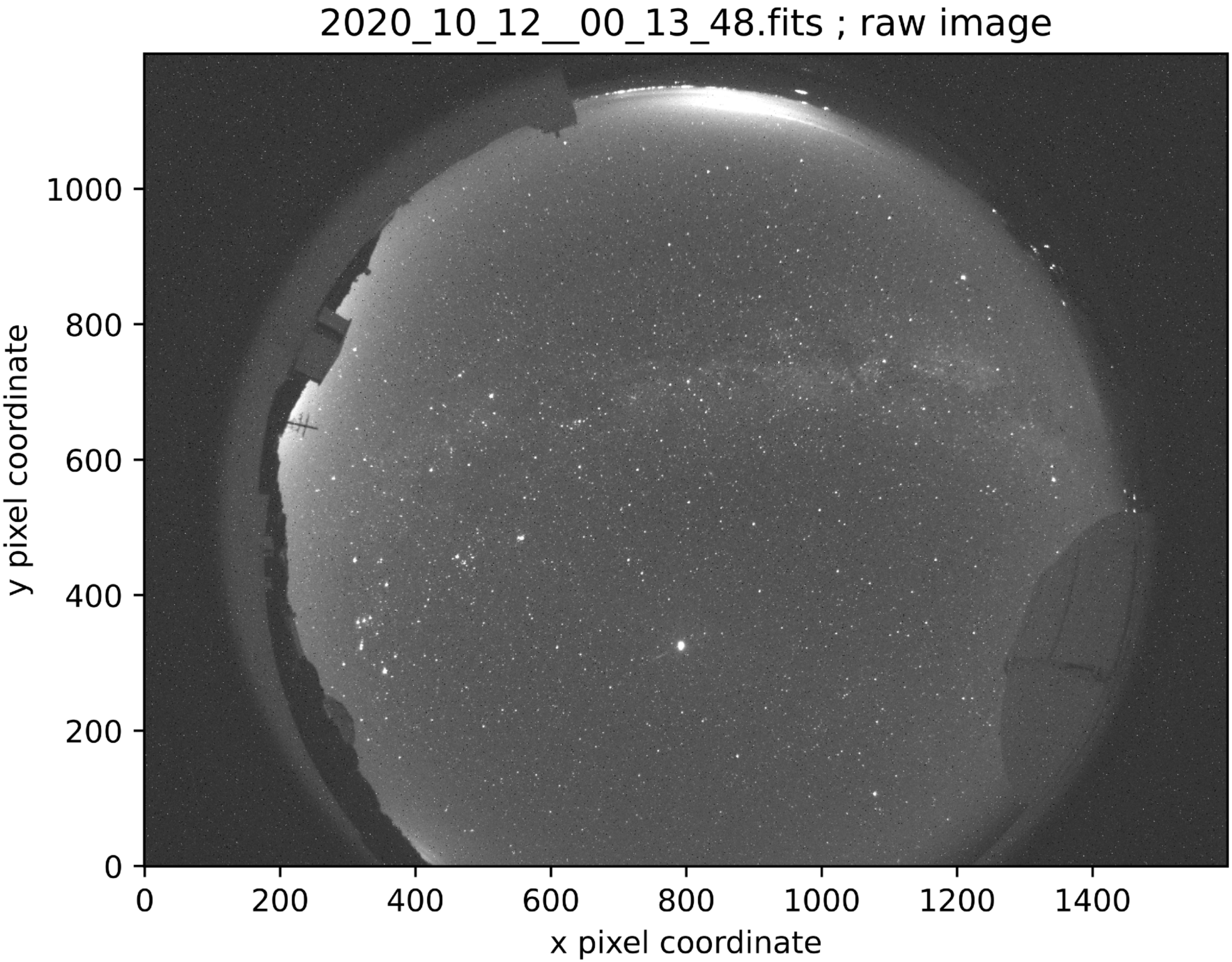
Photometry: 3rd image



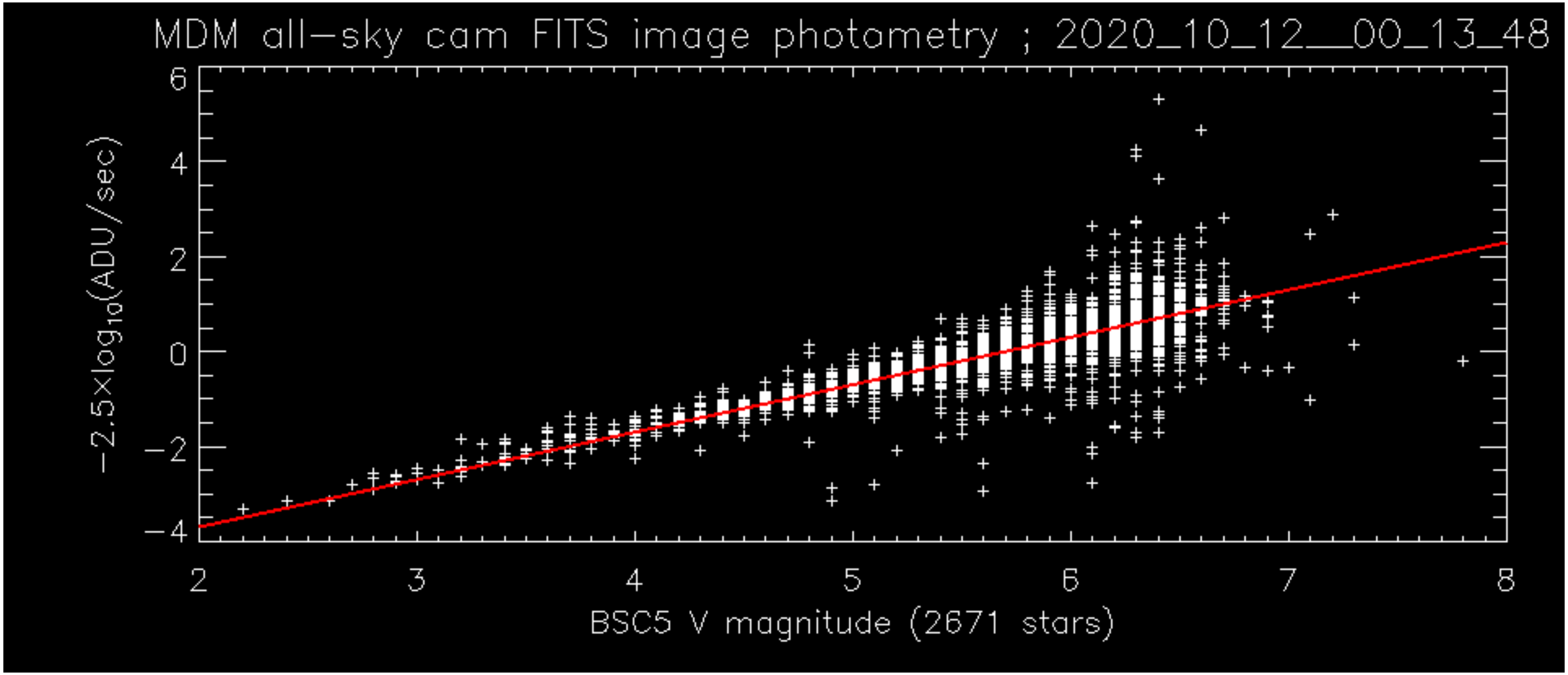
Photometry: 3rd image



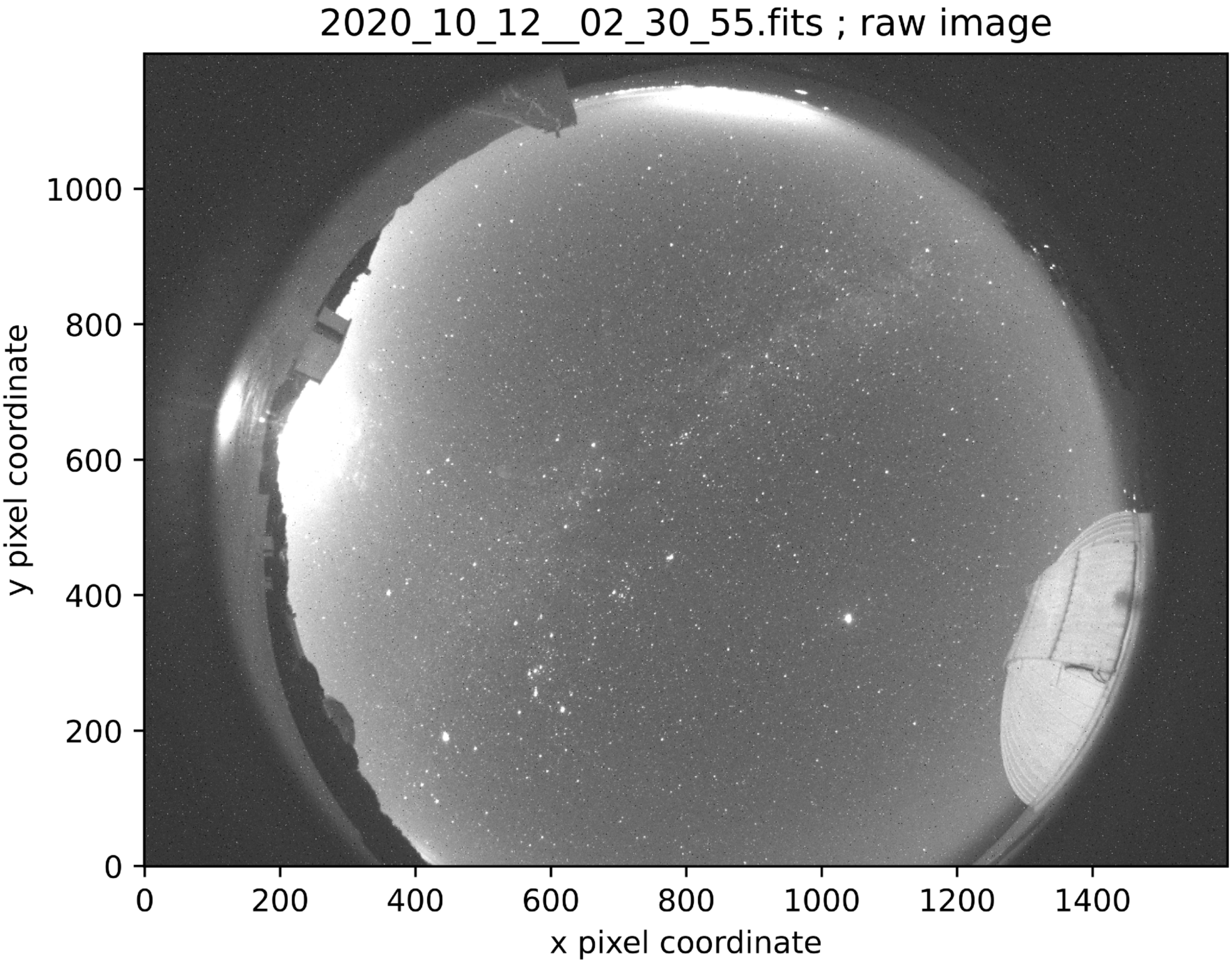
Photometry: 4th image



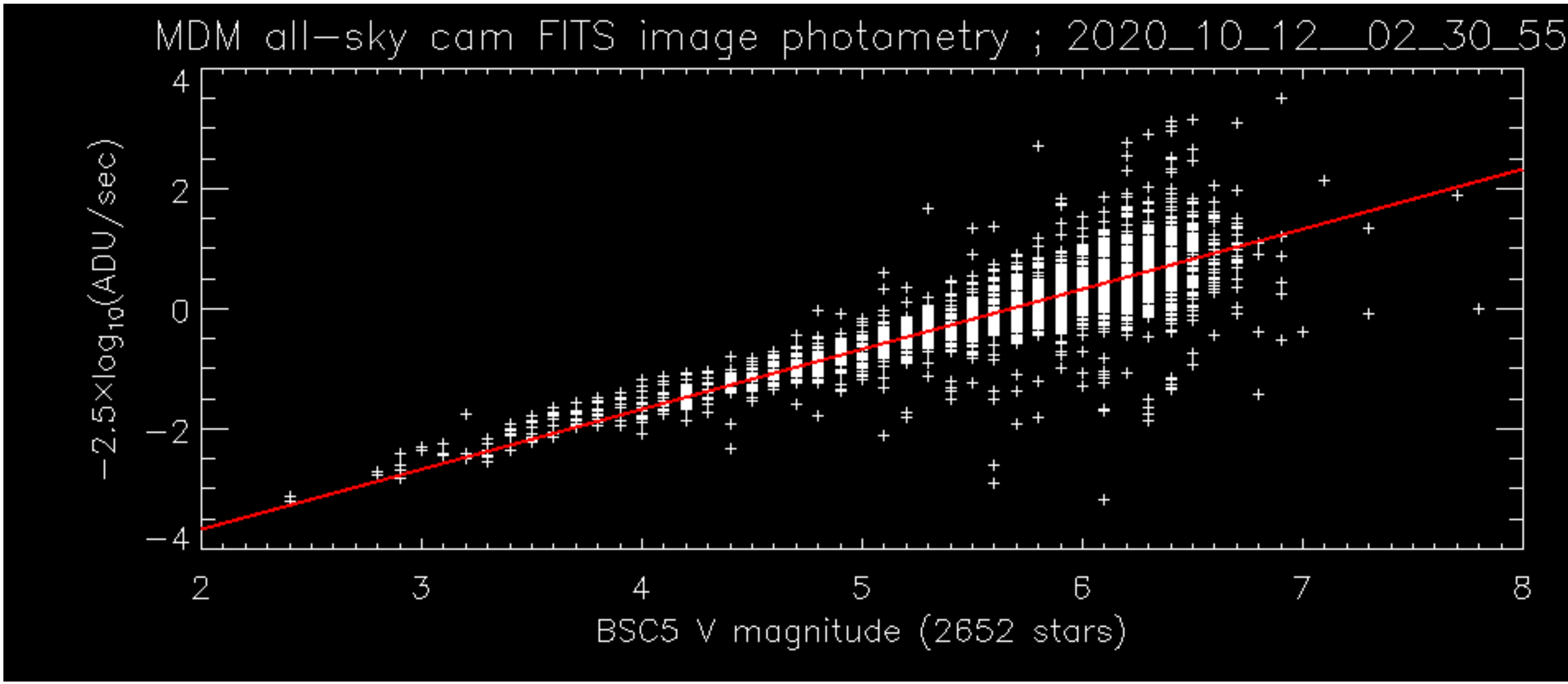
Photometry: 4th image



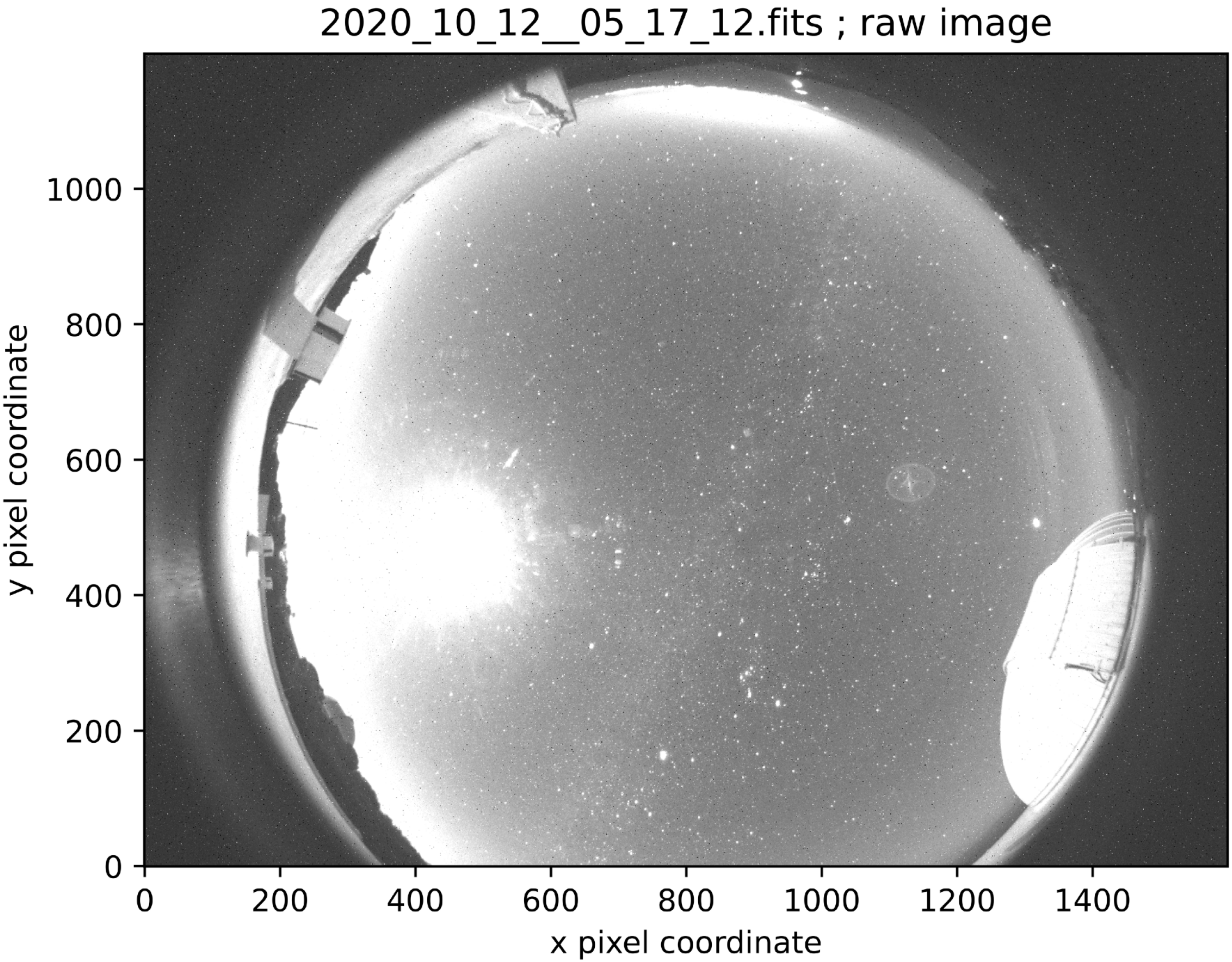
Photometry: 5th image



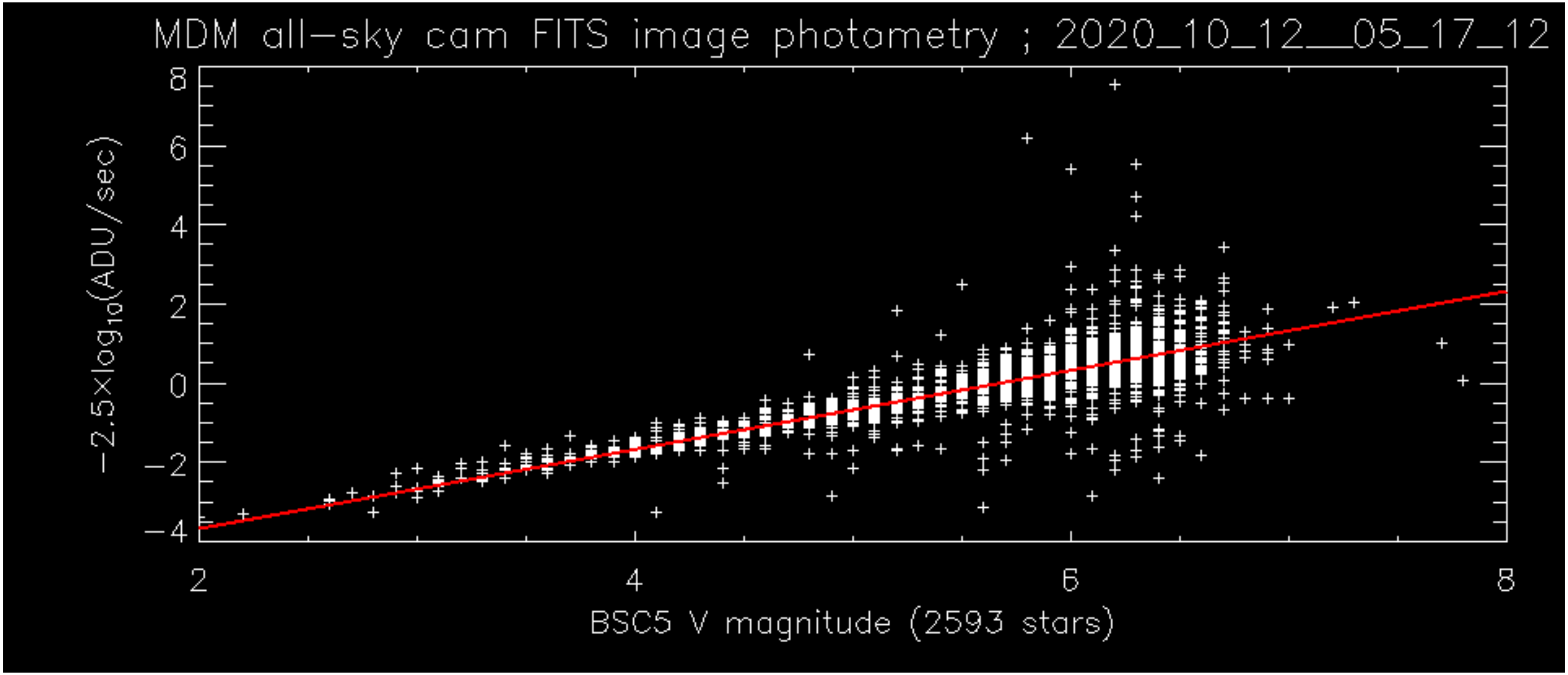
Photometry: 5th image



Photometry: 6th image



Photometry: 6th image

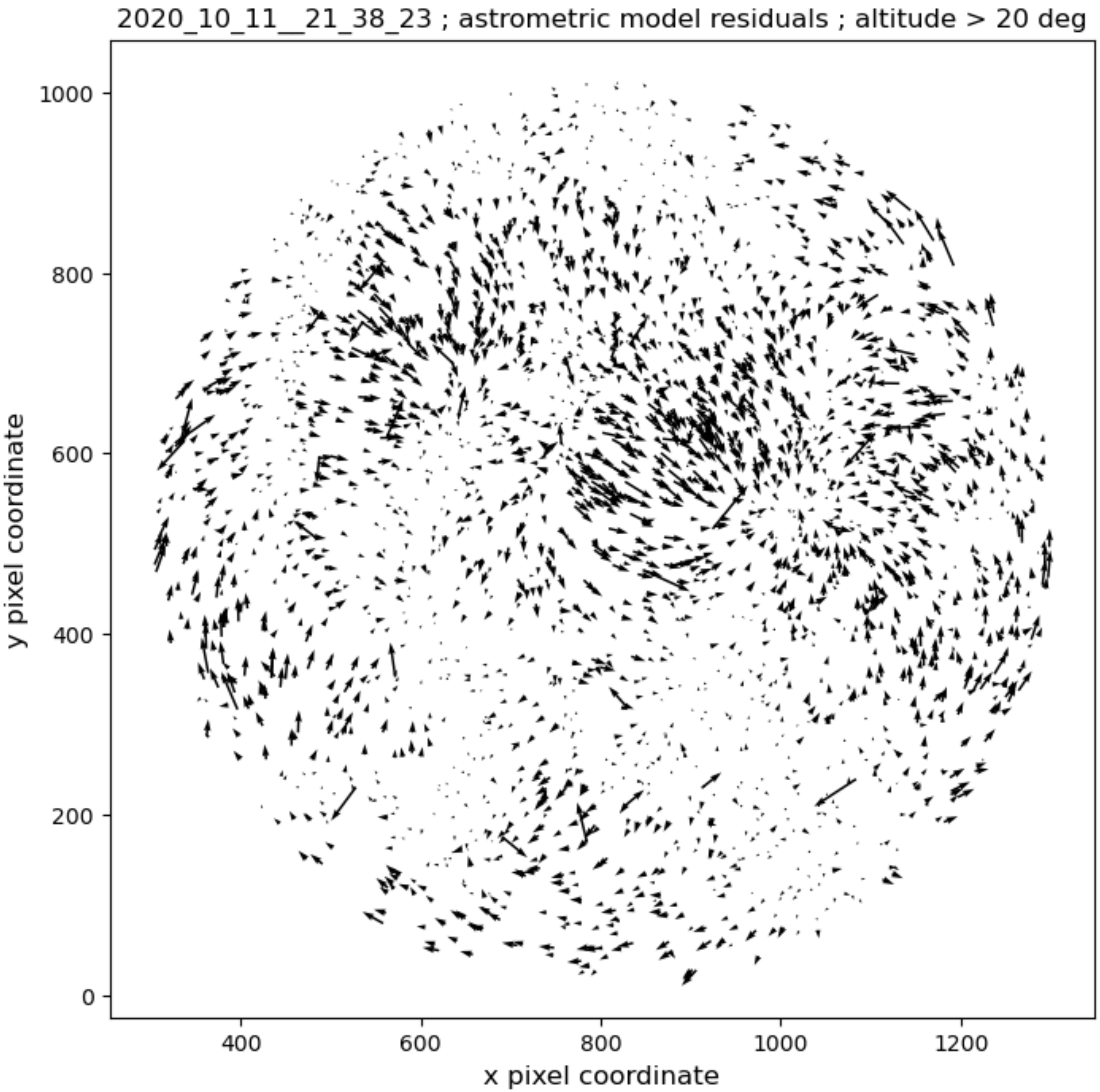


zeropoint magnitudes

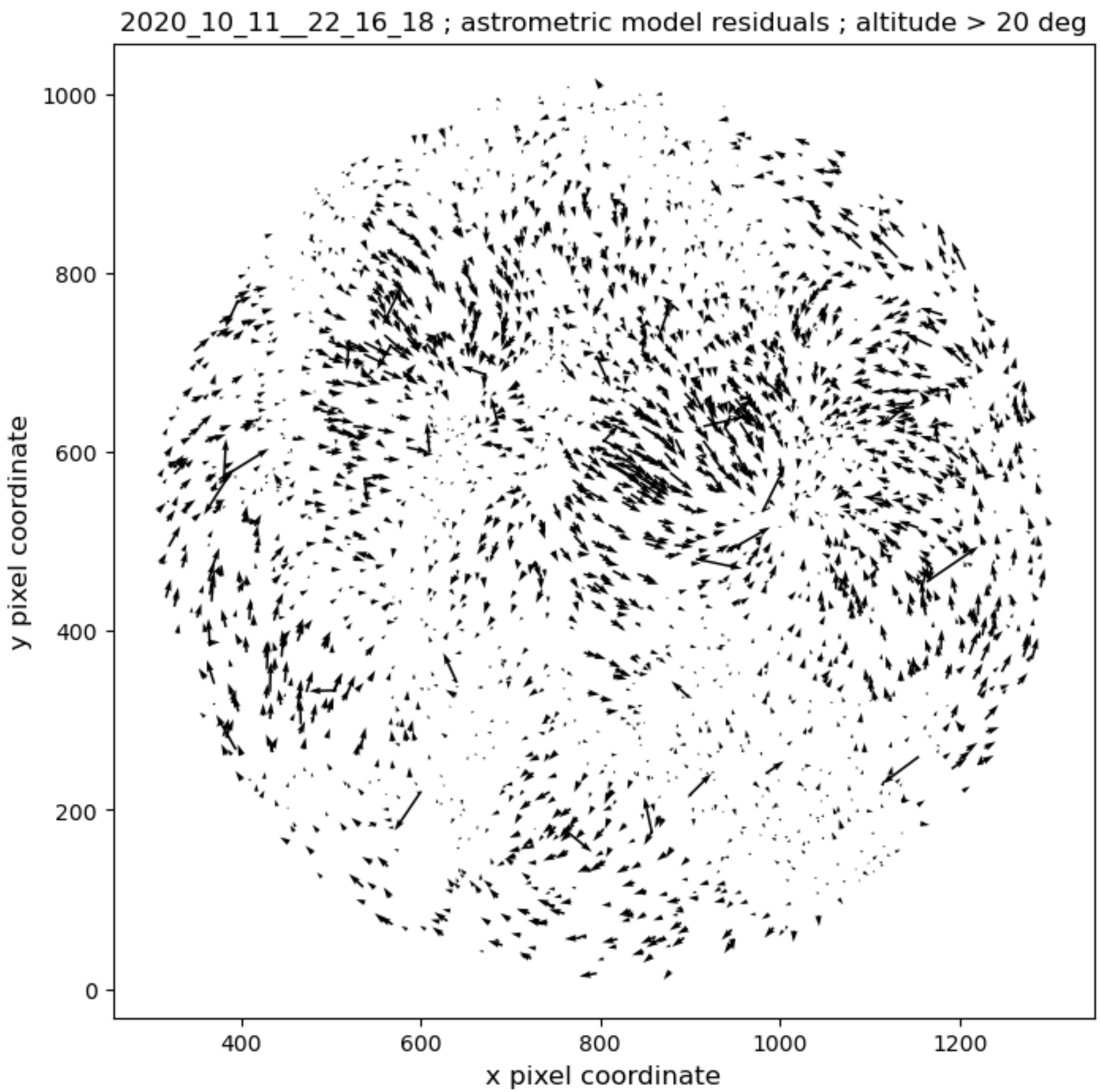
Filename	KPNO local date/time	V band zeropoint (1 ADU/s)	# of stars
2020_10_11__21_38_23.fits	2020-10-11 21:37:14.72	5.662	2657
2020_10_11__22_16_18.fits	2020-10-11 22:15:09.56	5.667	2596
2020_10_11__23_17_30.fits	2020-10-11 23:16:21.45	5.663	2623
2020_10_12__00_13_48.fits	2020-10-12 00:12:39.80	5.677	2671
2020_10_12__02_30_55.fits	2020-10-12 02:29:46.69	5.670	2652
2020_10_12__05_17_12.fits	2020-10-12 05:16:03.74	5.670	2593

- zeropoints are with respect to a 2 pixel radius aperture

astrometric residuals



astrometric residuals



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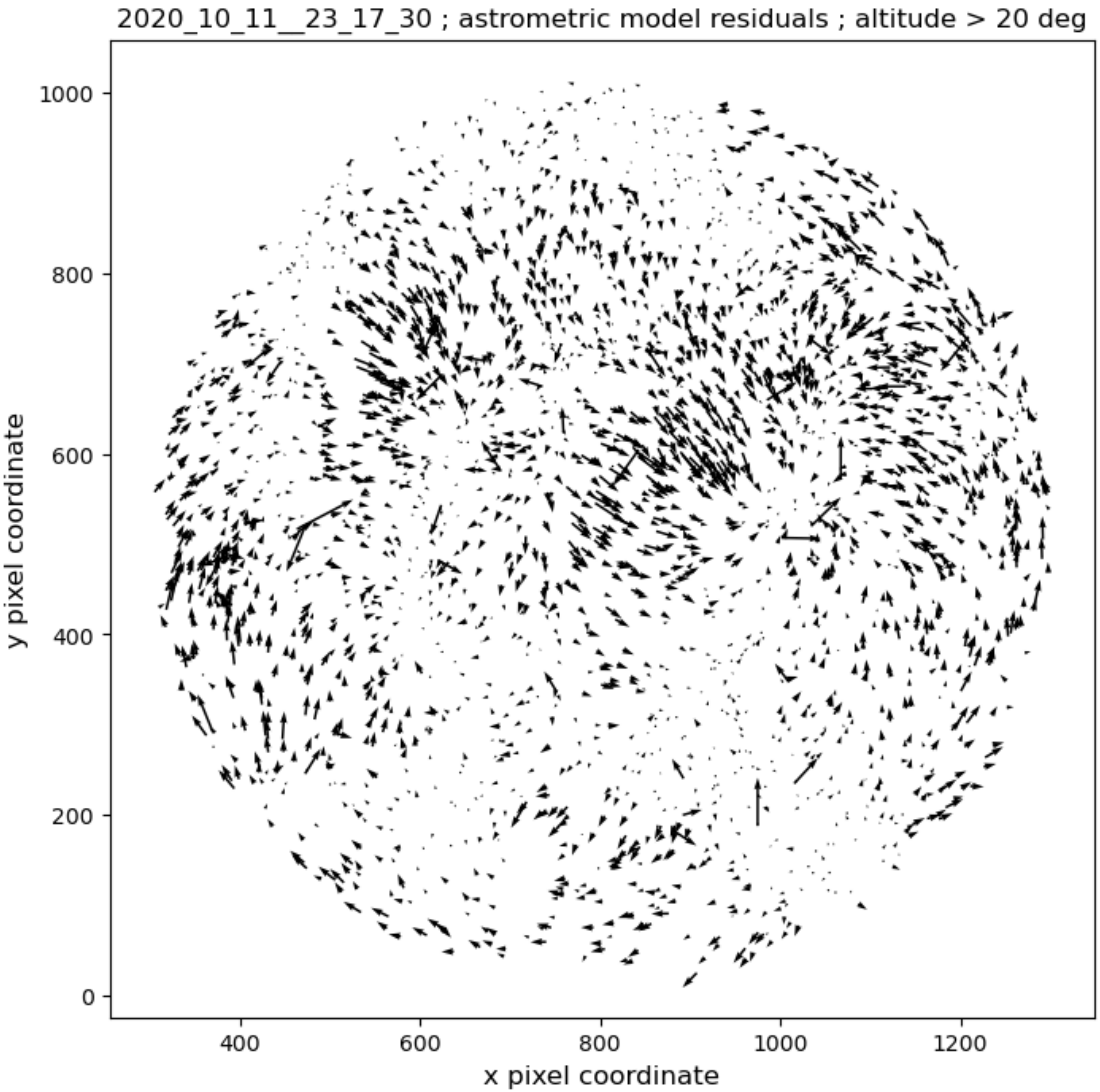

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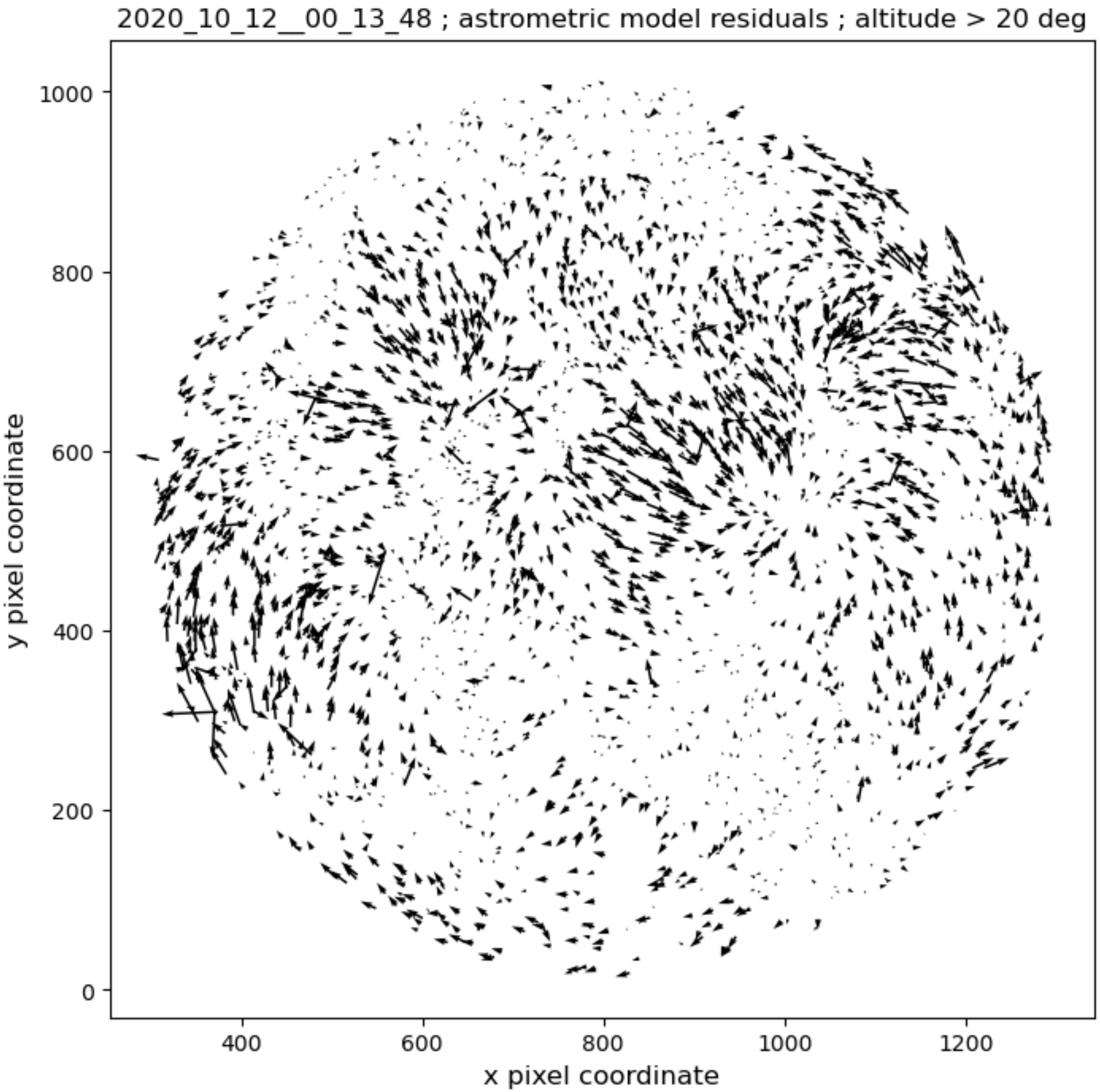
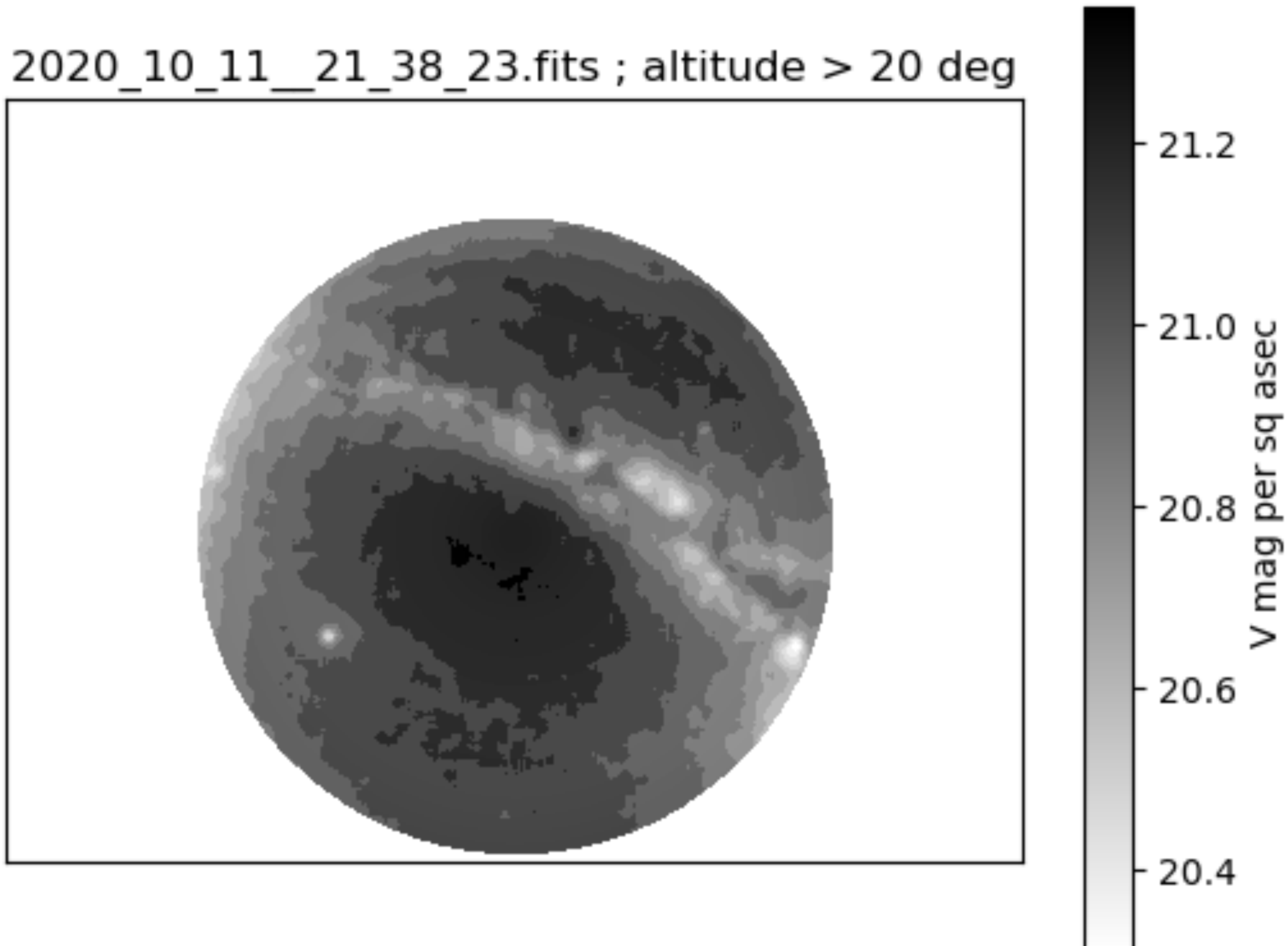


astrometric residuals

- The astrometric residuals look consistent from one image to another throughout the night
- Assuming that these residuals are stable on longer timescales, one could create an empirical look-up table for incorporation into a refined version of the astrometric model

Sky brightness maps

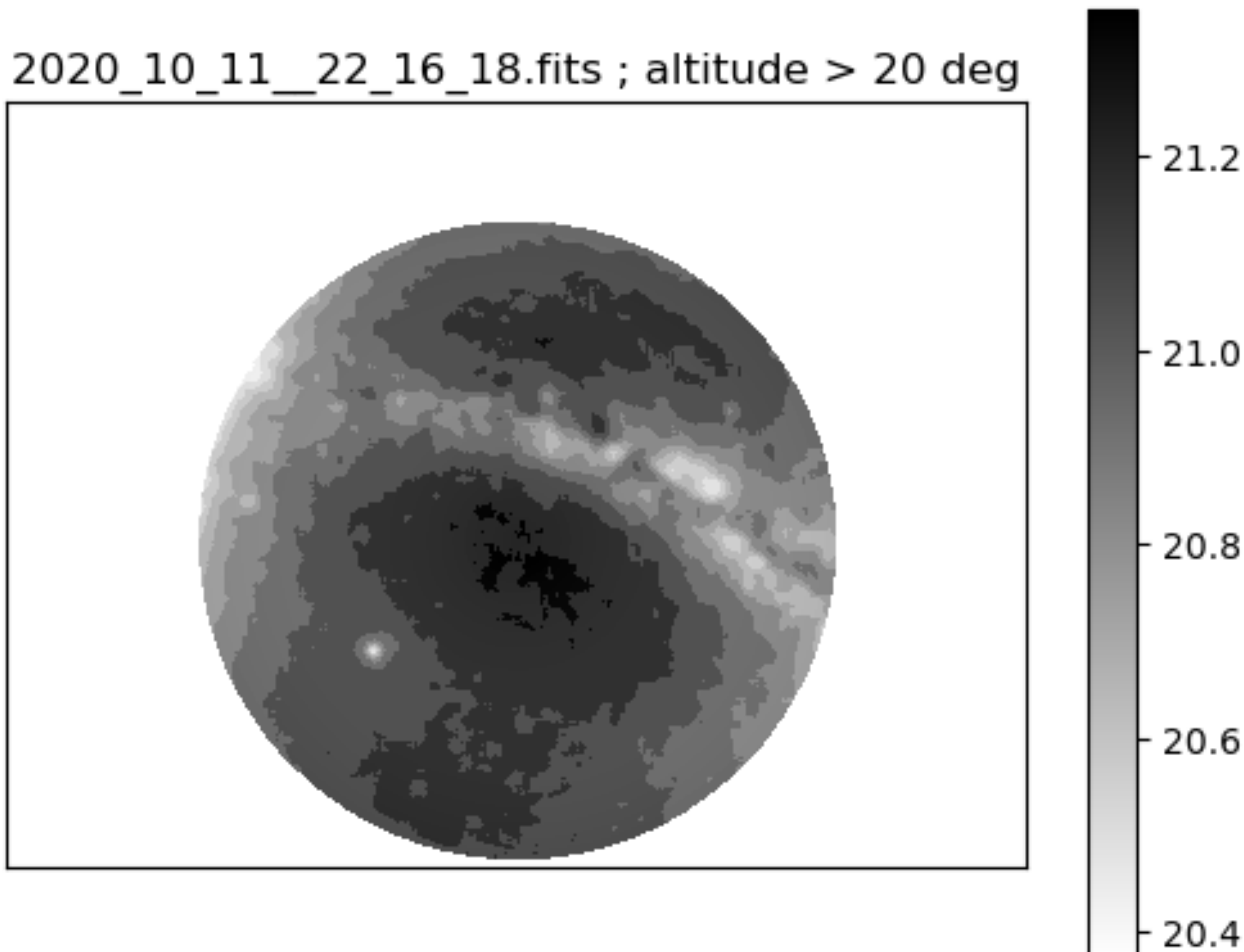


~3.2 degree median filter

assumes a zeropoint whereby 1 ADU/s corresponds to V = 5.66

accounts for spatially varying pixel solid angle

Sky brightness maps



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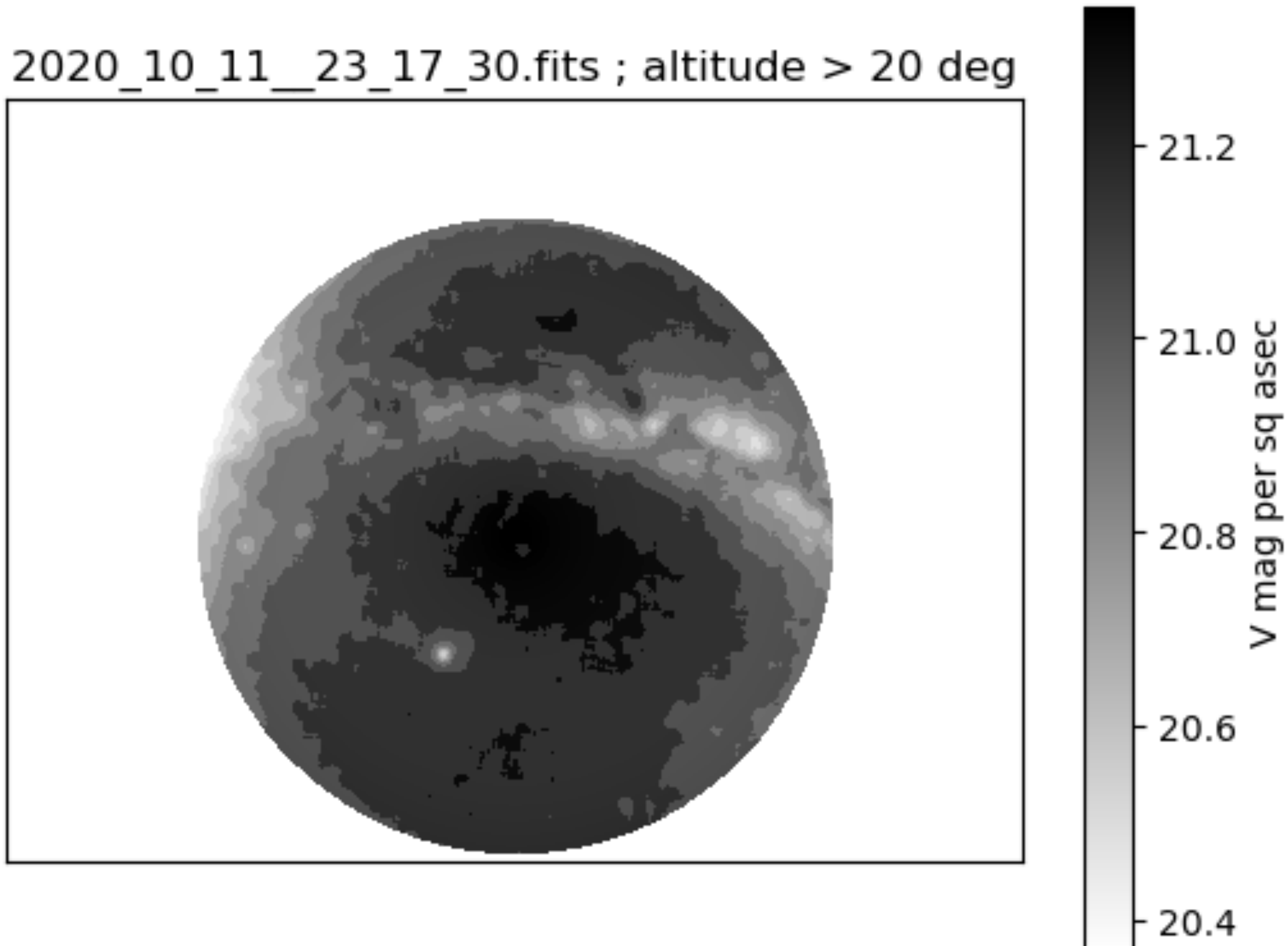

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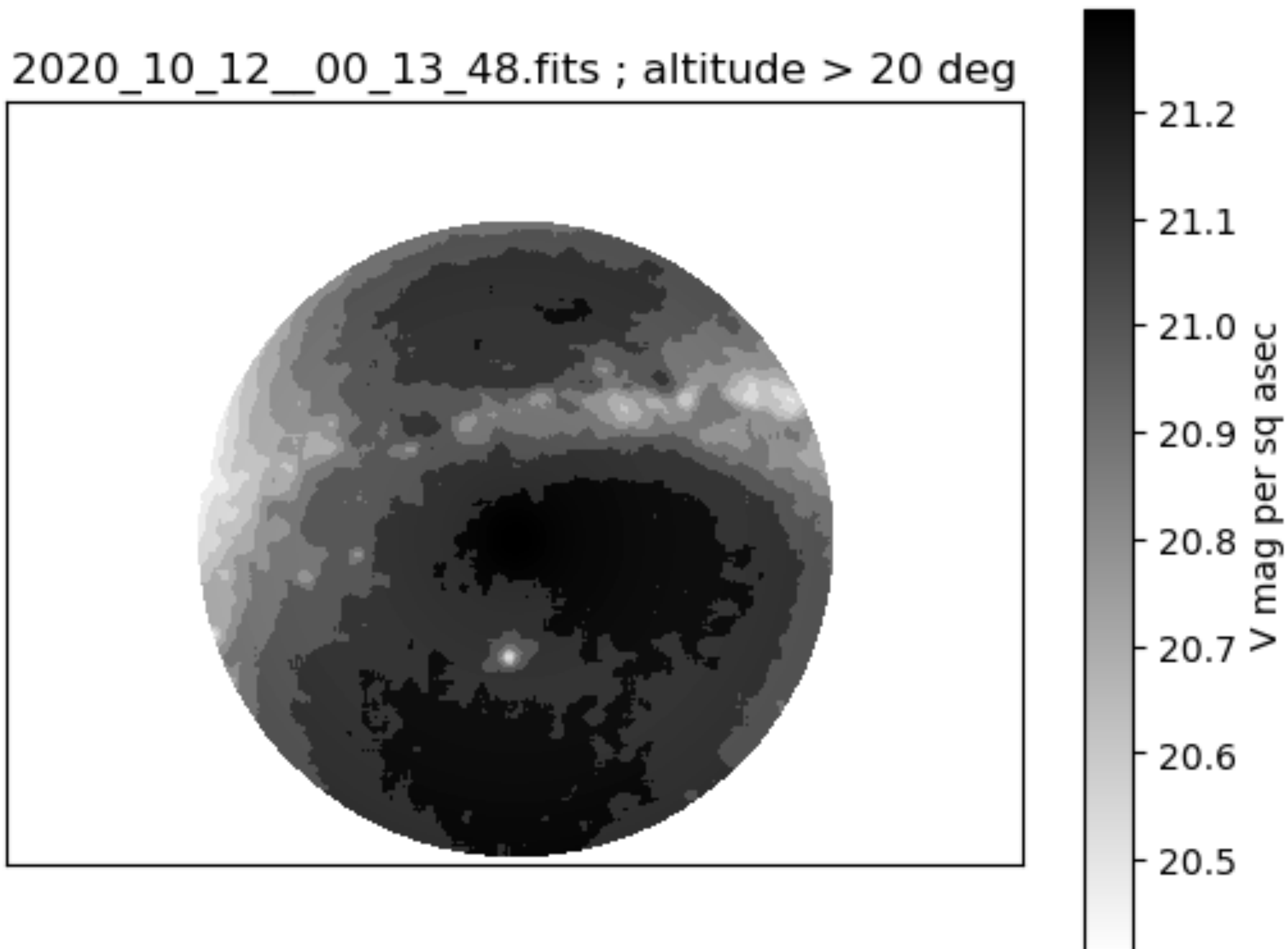

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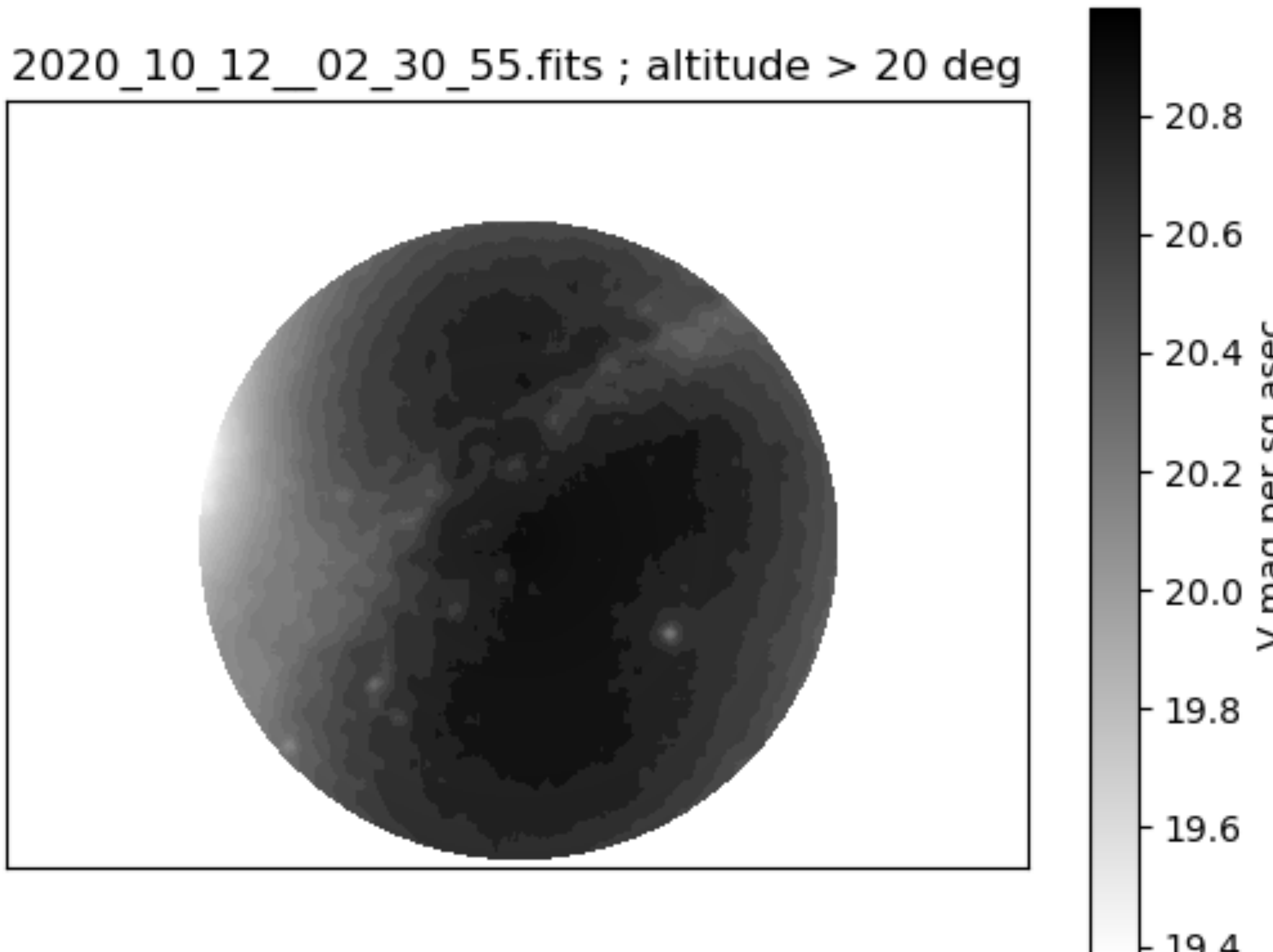

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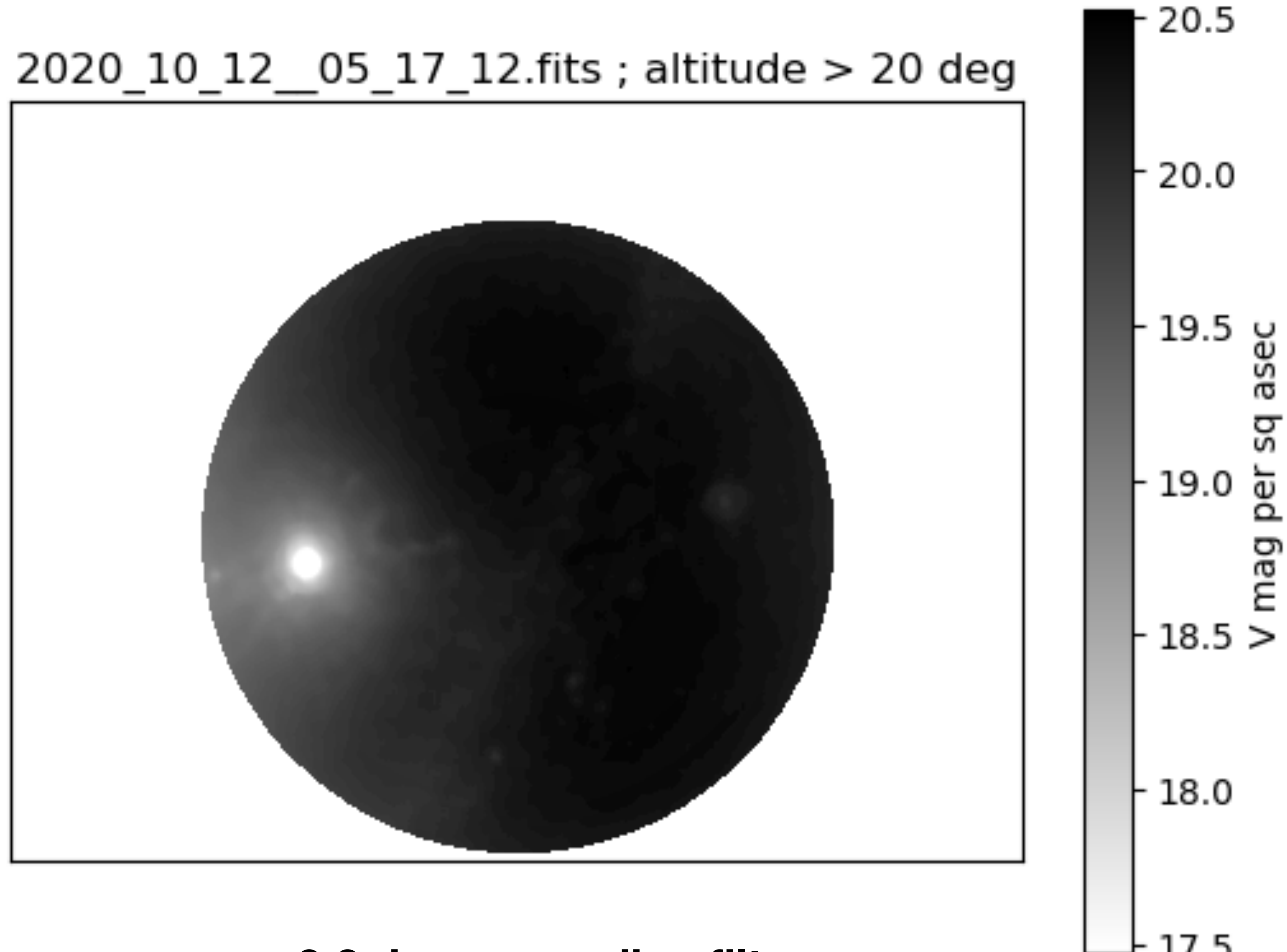

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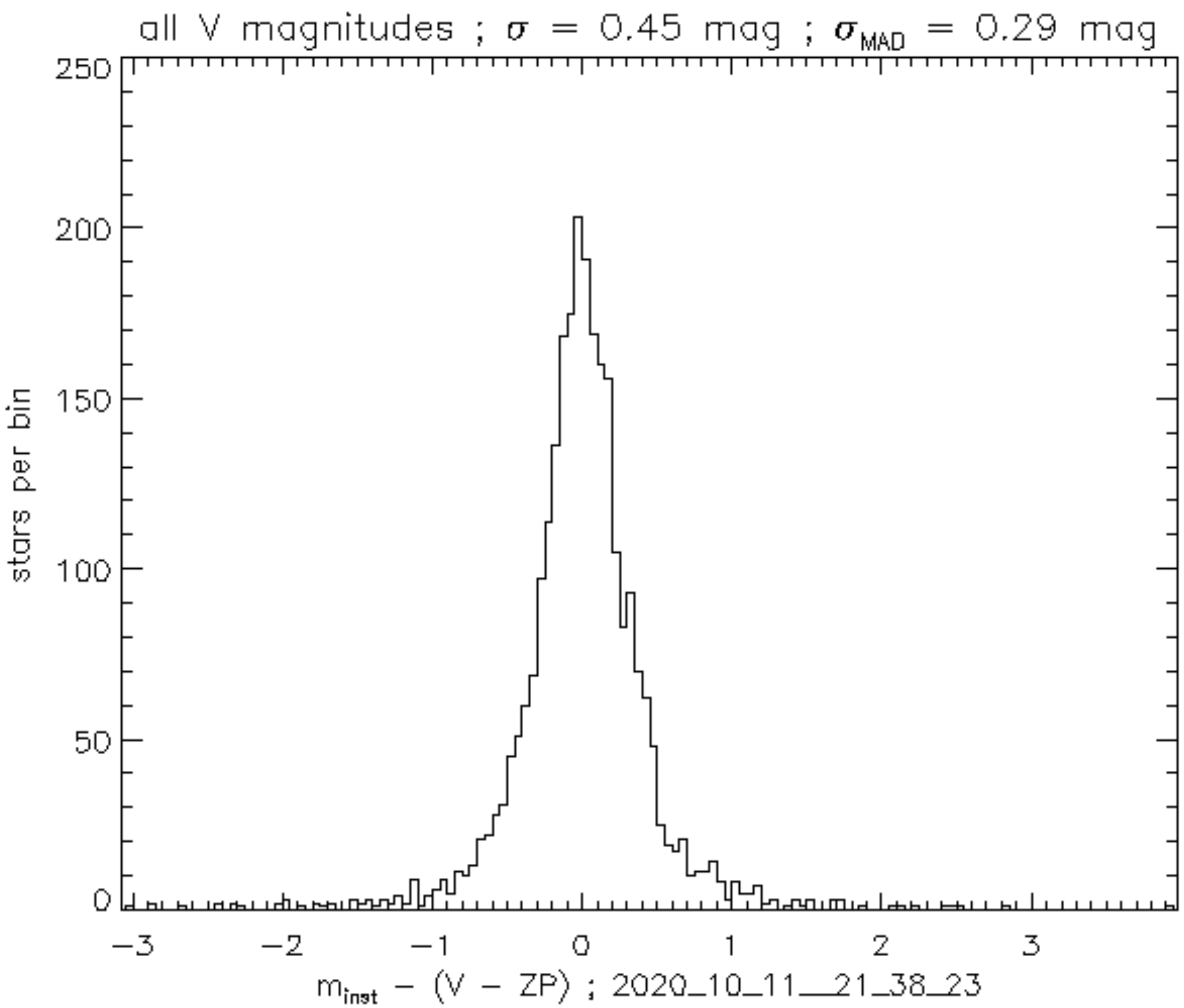
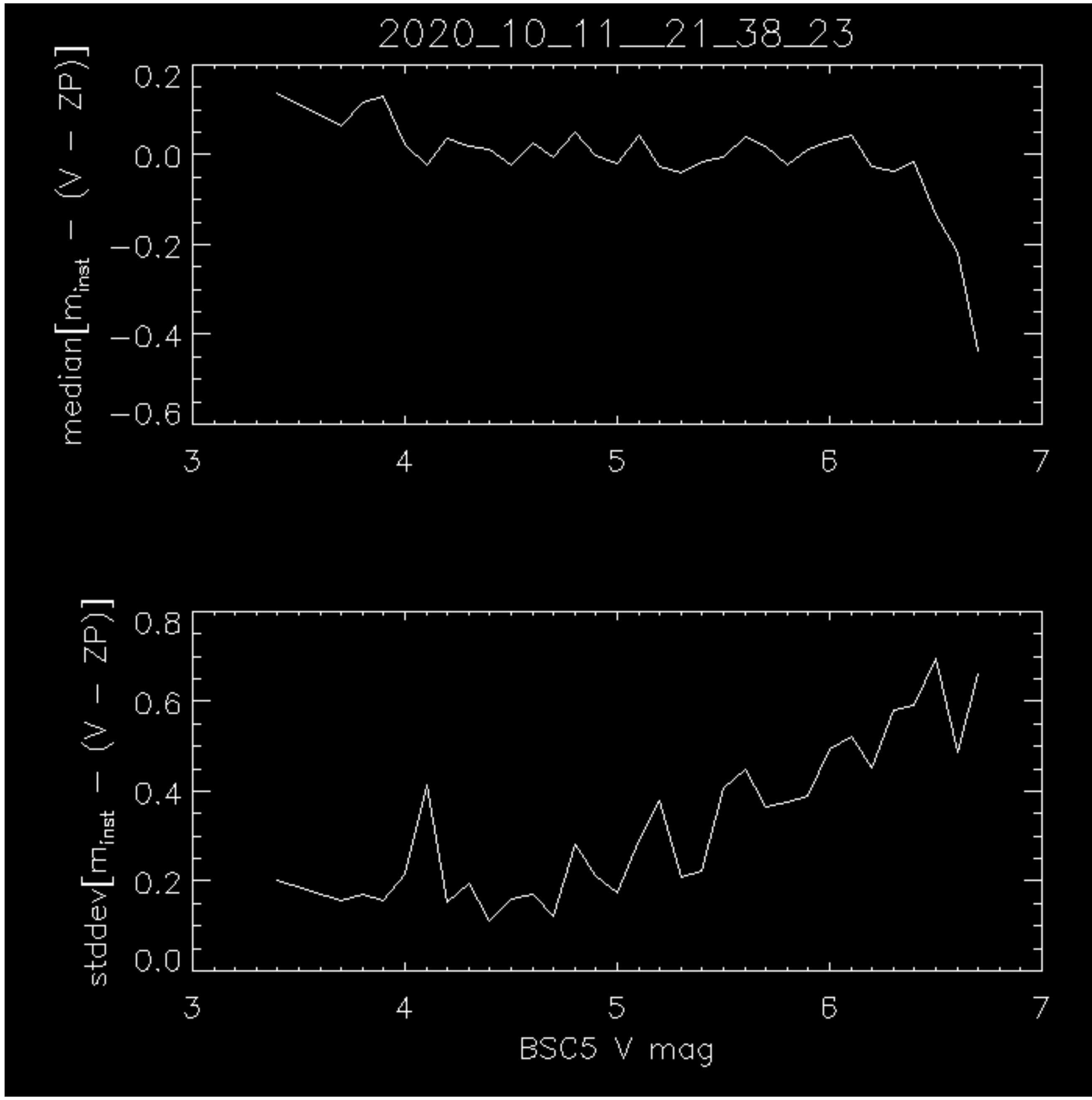
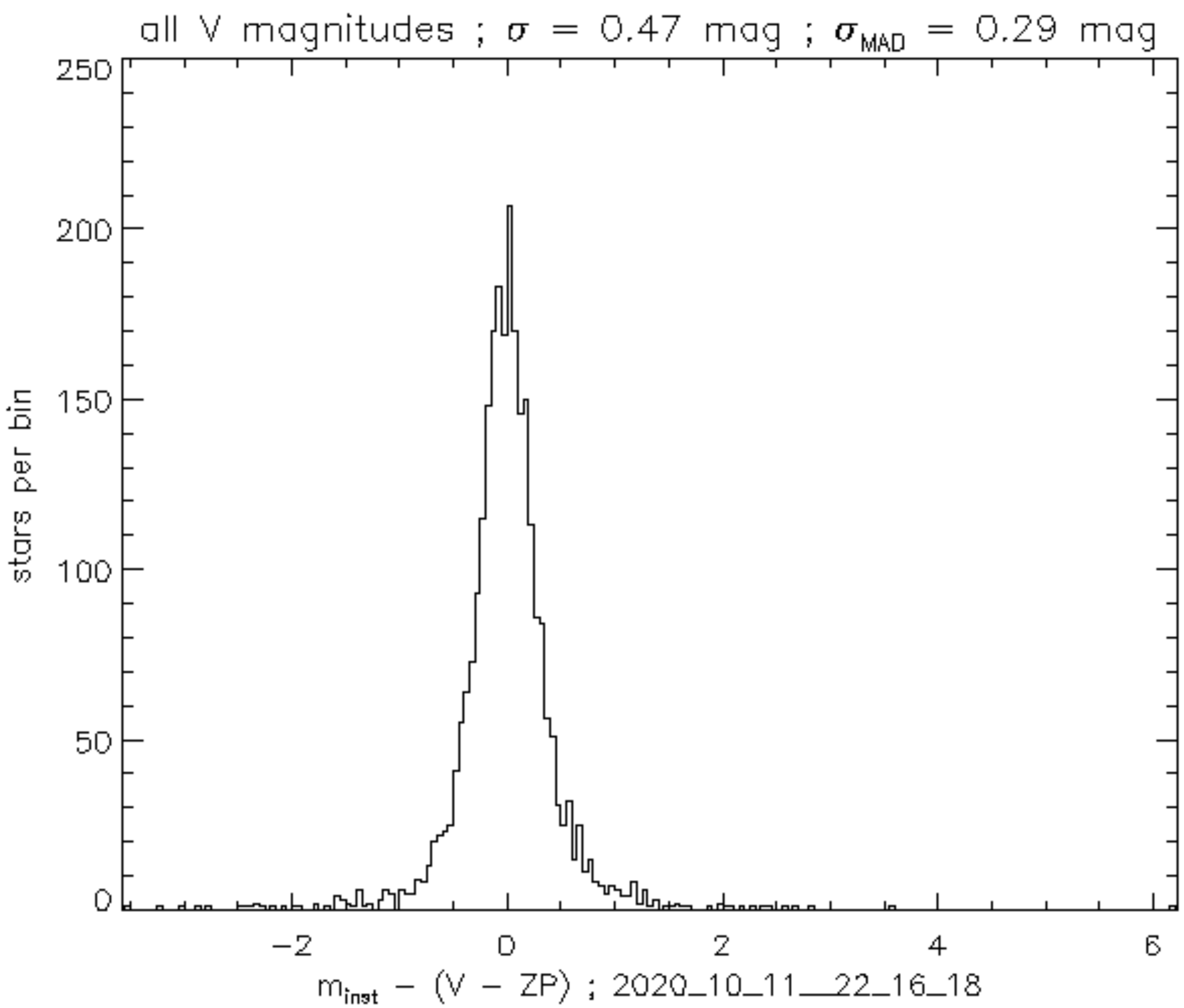
Mapping the transparency?

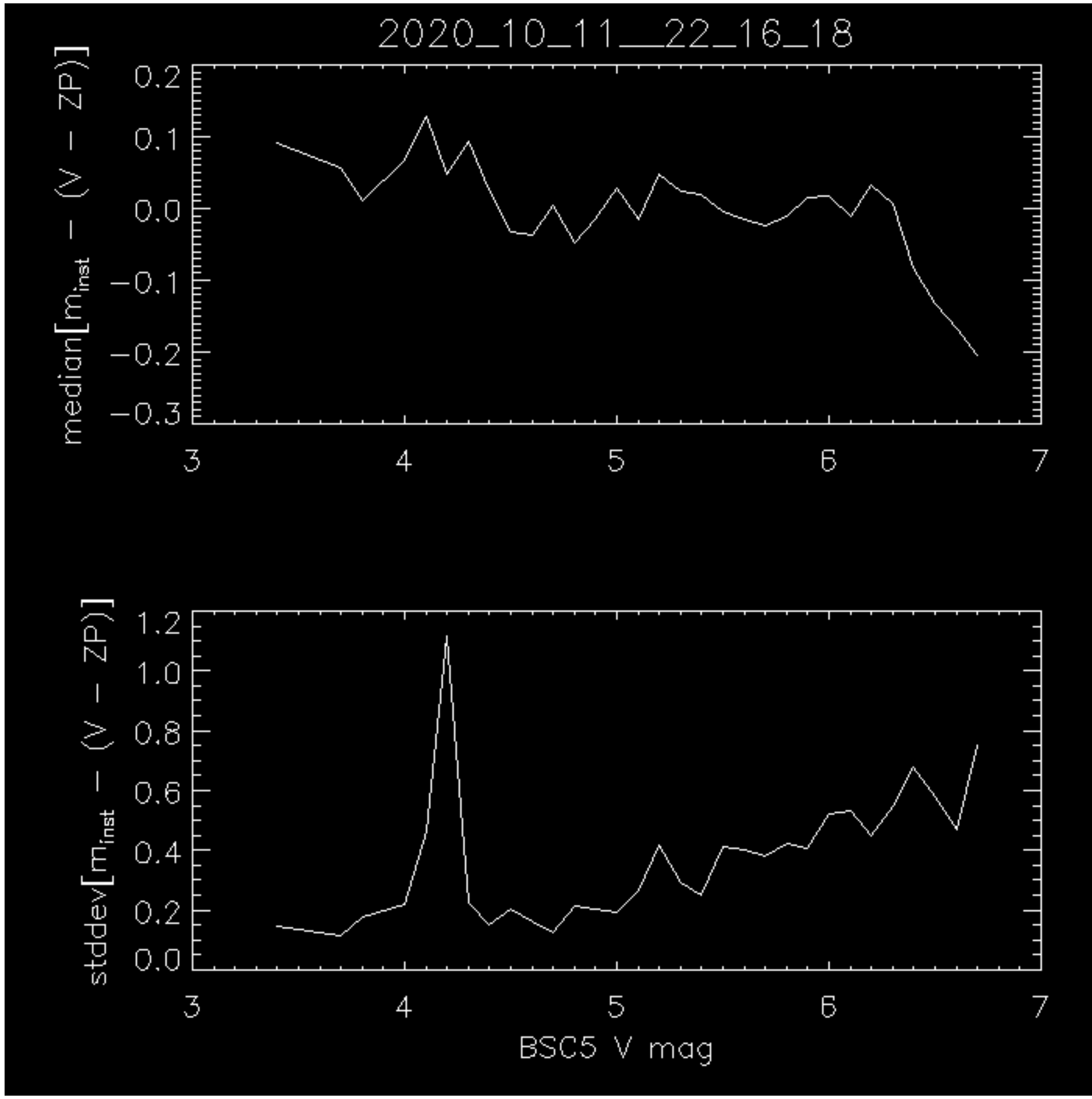




The per-star scatter of ~0.45 mags relative to the overall zeropoint is very large; this scatter appears to reach a floor of ~0.15-0.2 mags at the bright end.

Mapping the transparency?





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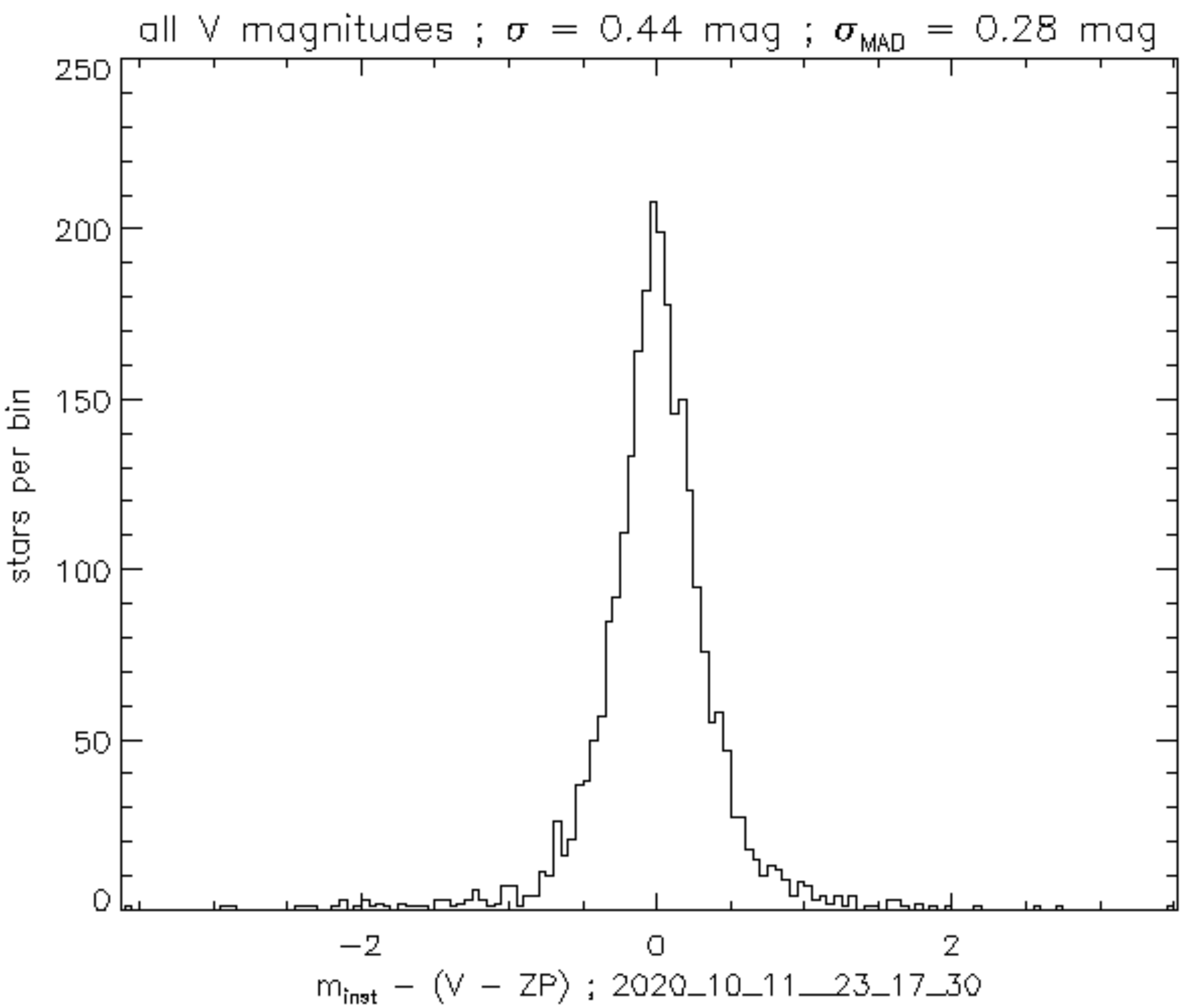

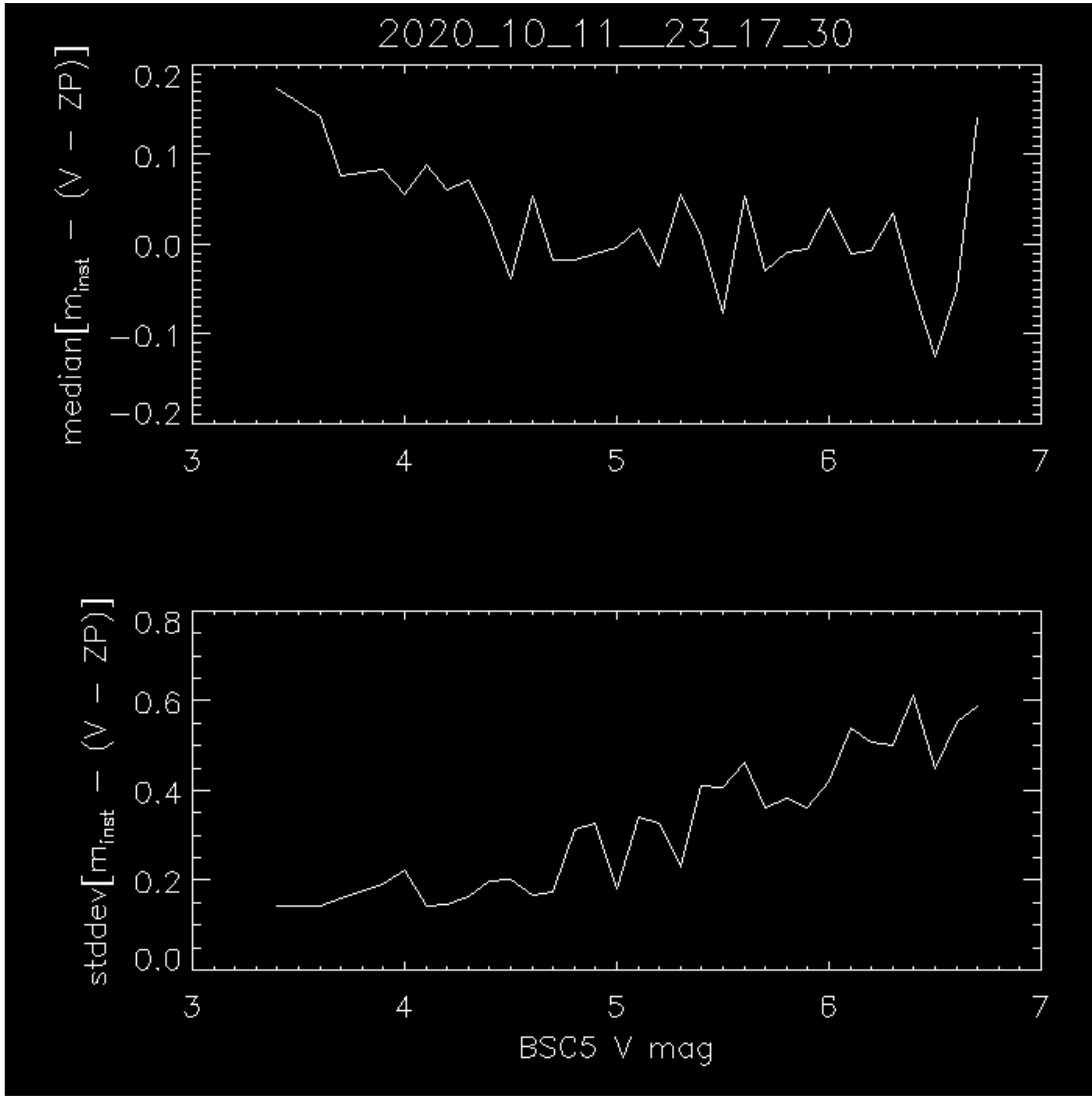

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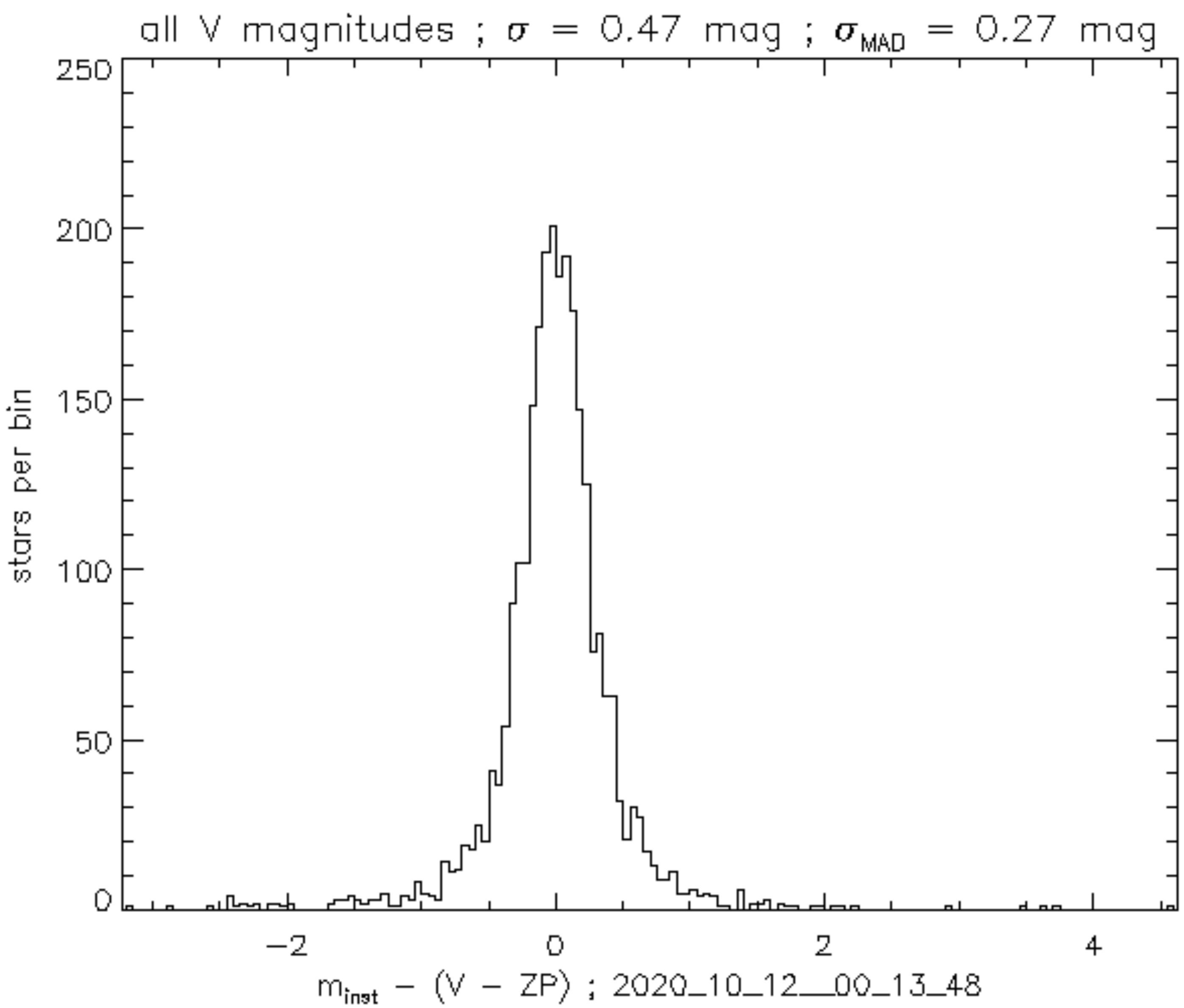

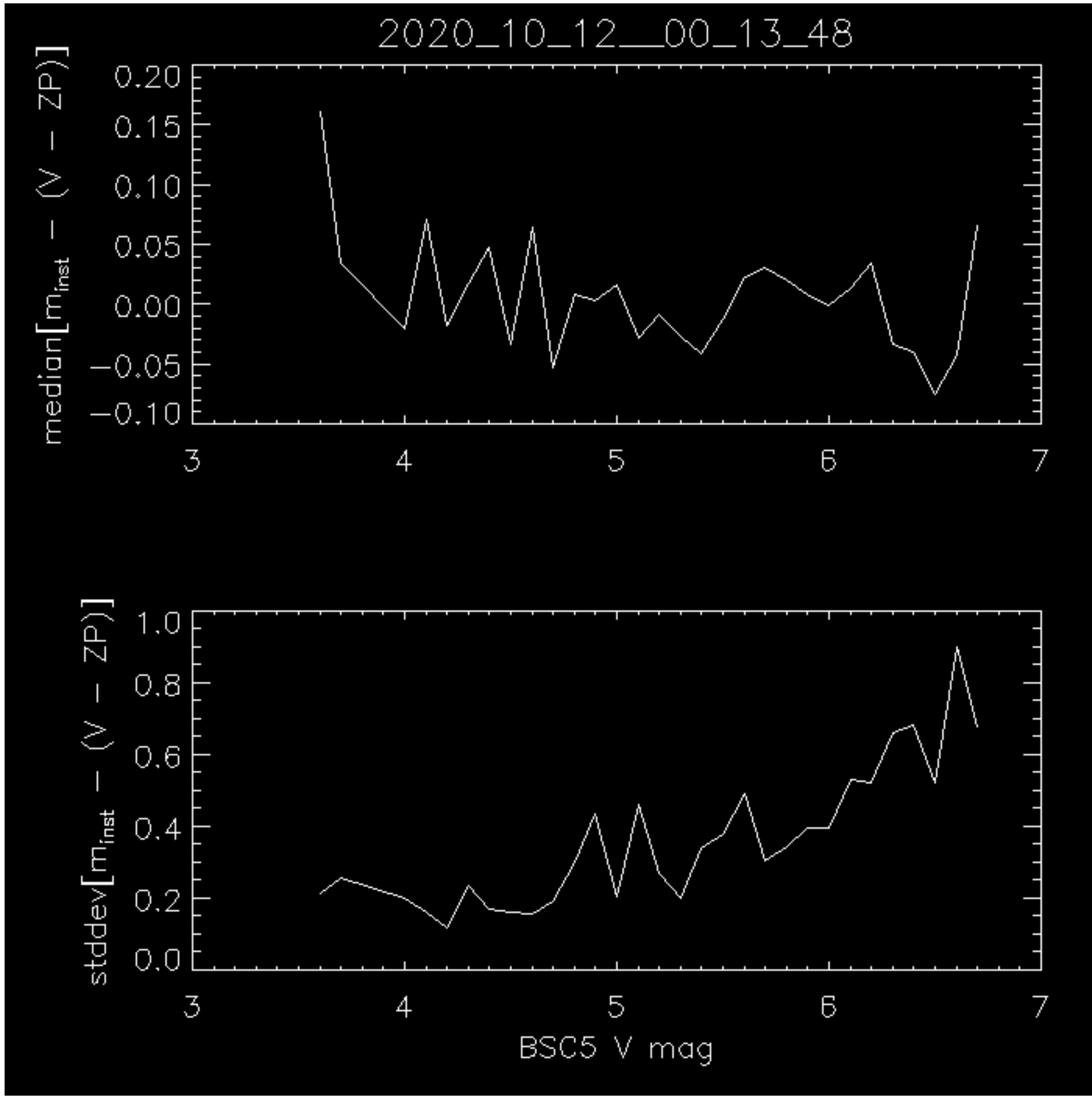

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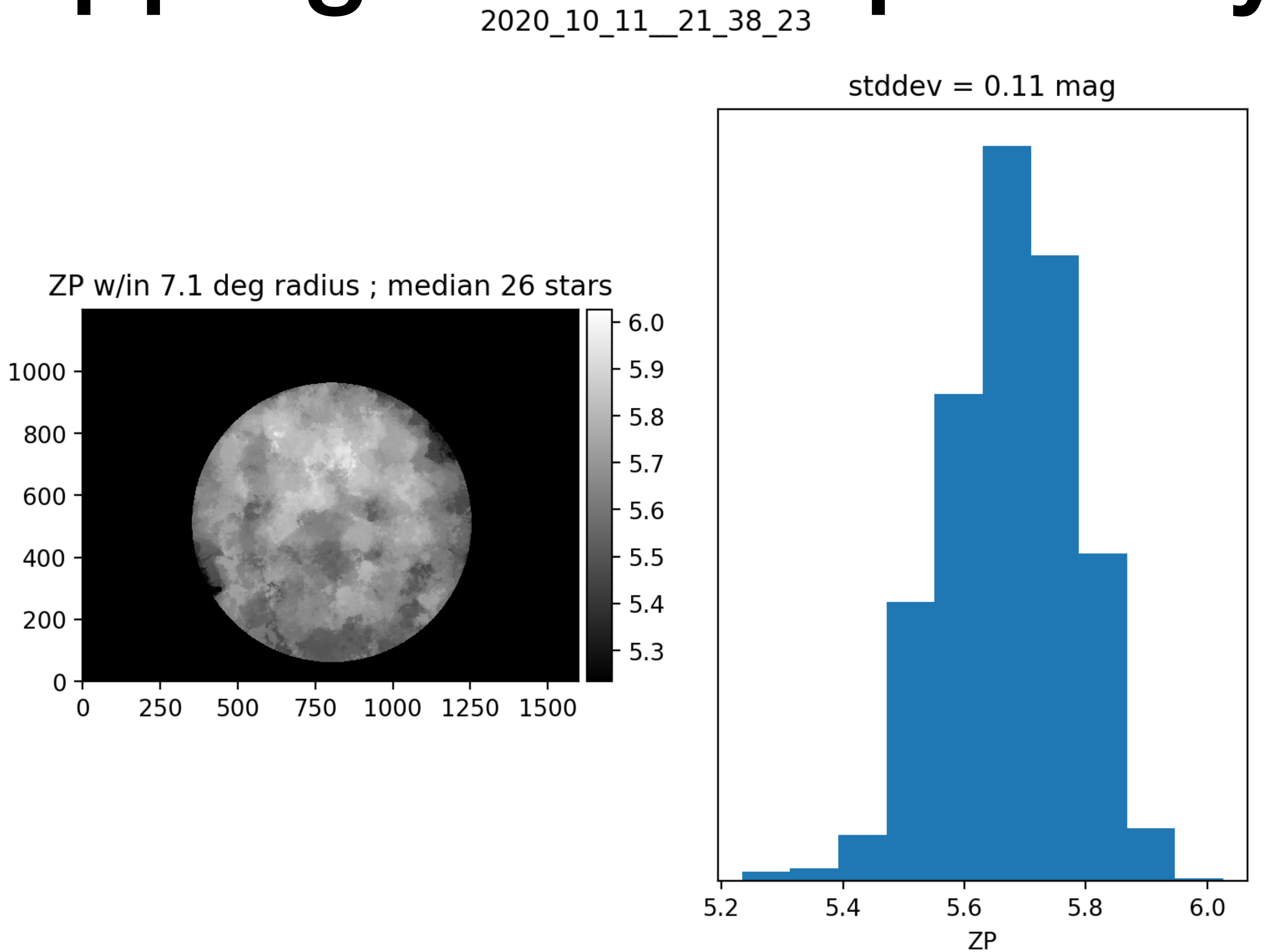
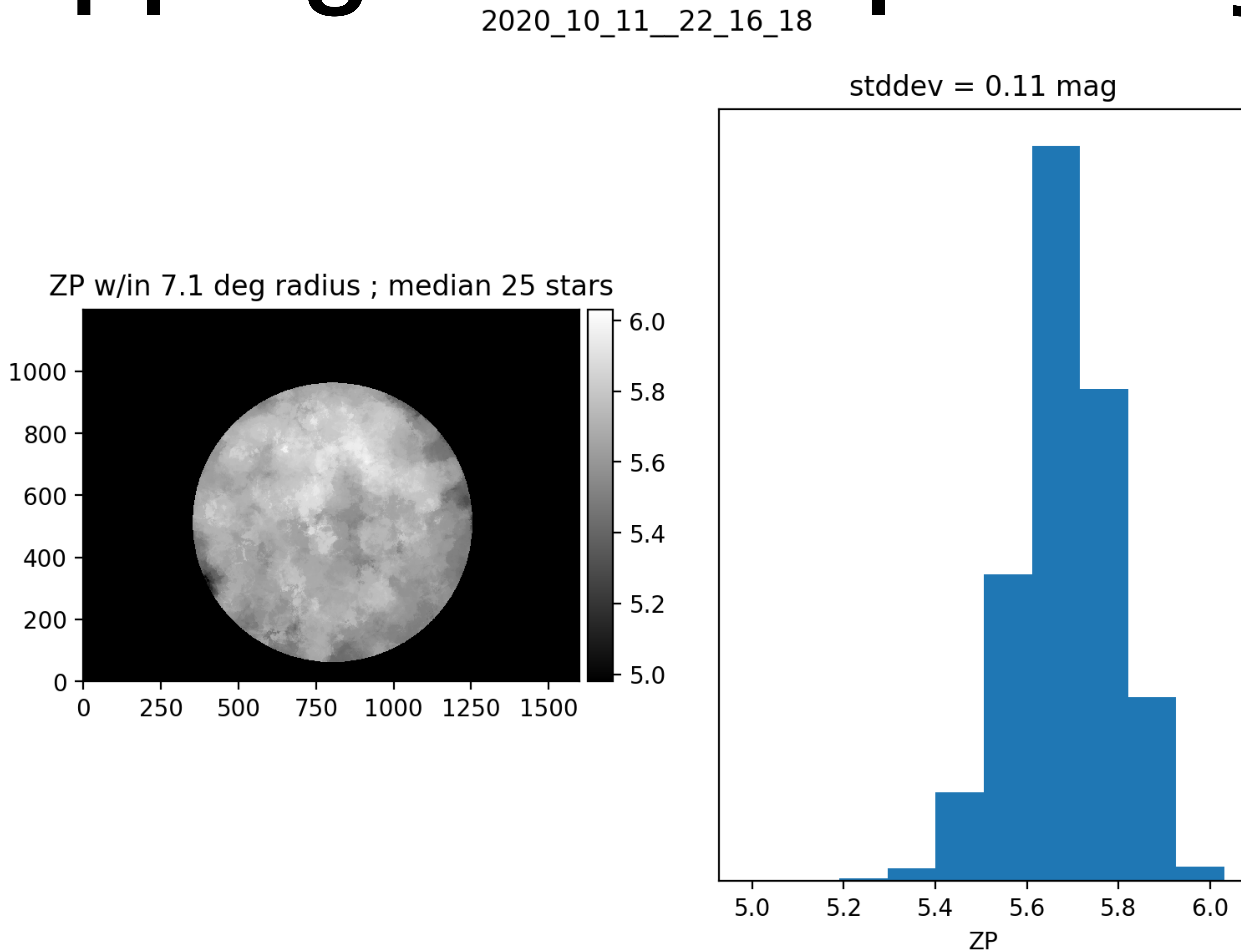


- The variation of the zeropoint measured in different ~160 sq deg sky patches (~25 stars per patch) seems much larger than we'd like in order to map real transparency variations (assuming conditions on this example night were indeed photometric).
- stddev = 0.1-0.11 mags matches reasonably well with 0.45 mags / sqrt(25) = 0.09 mags, i.e. the per-star stddev divided by the square root of the number of stars per sky patch

Mapping the transparency?



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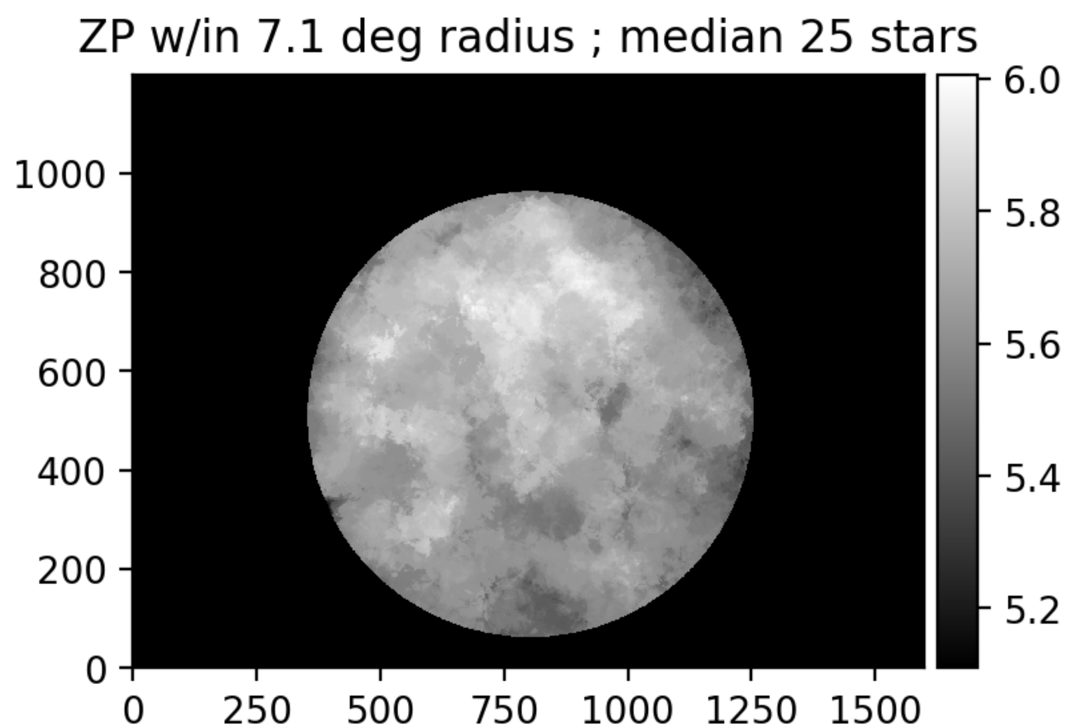
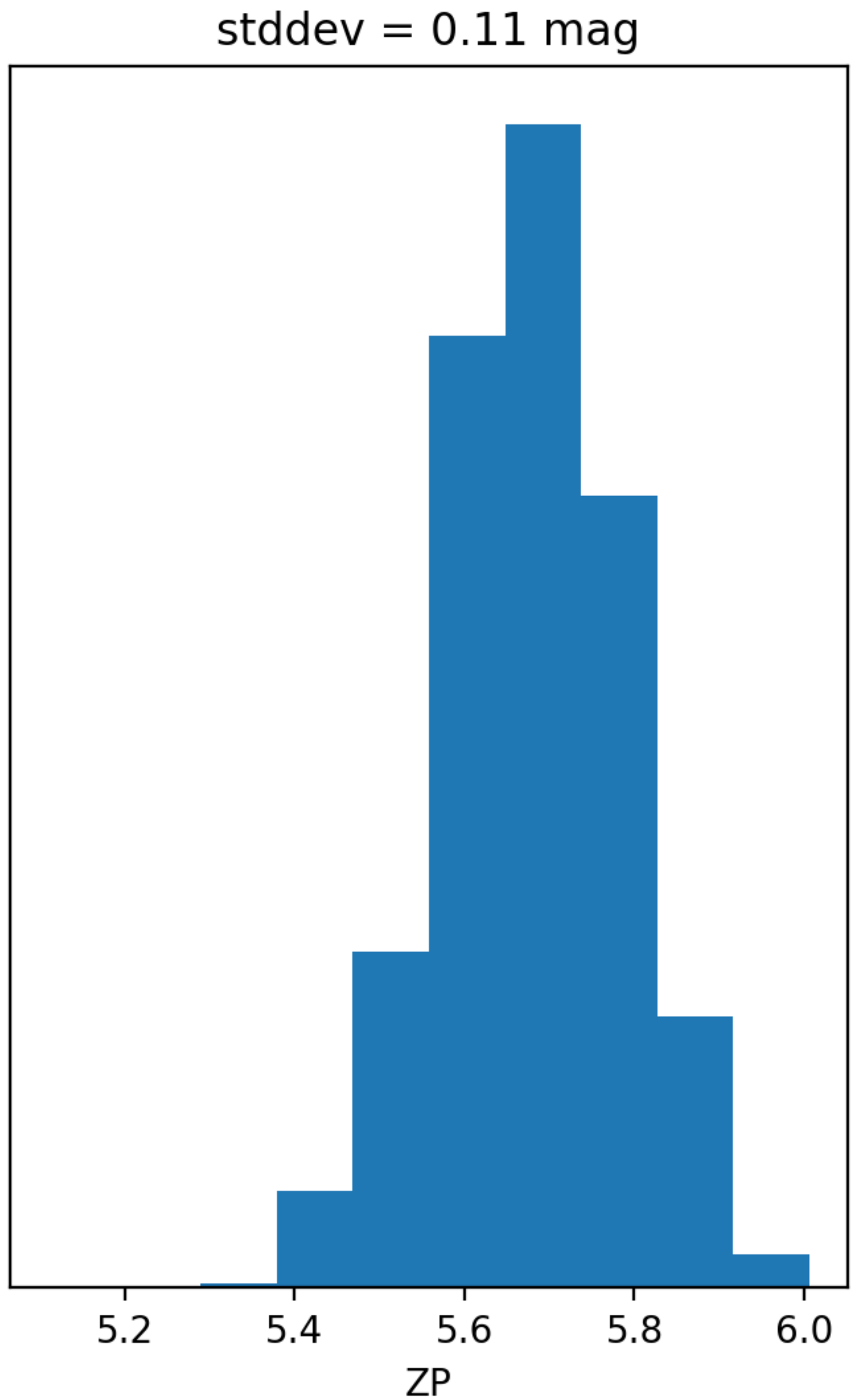
Mapping the transparency?

2020_10_11__23_17_30





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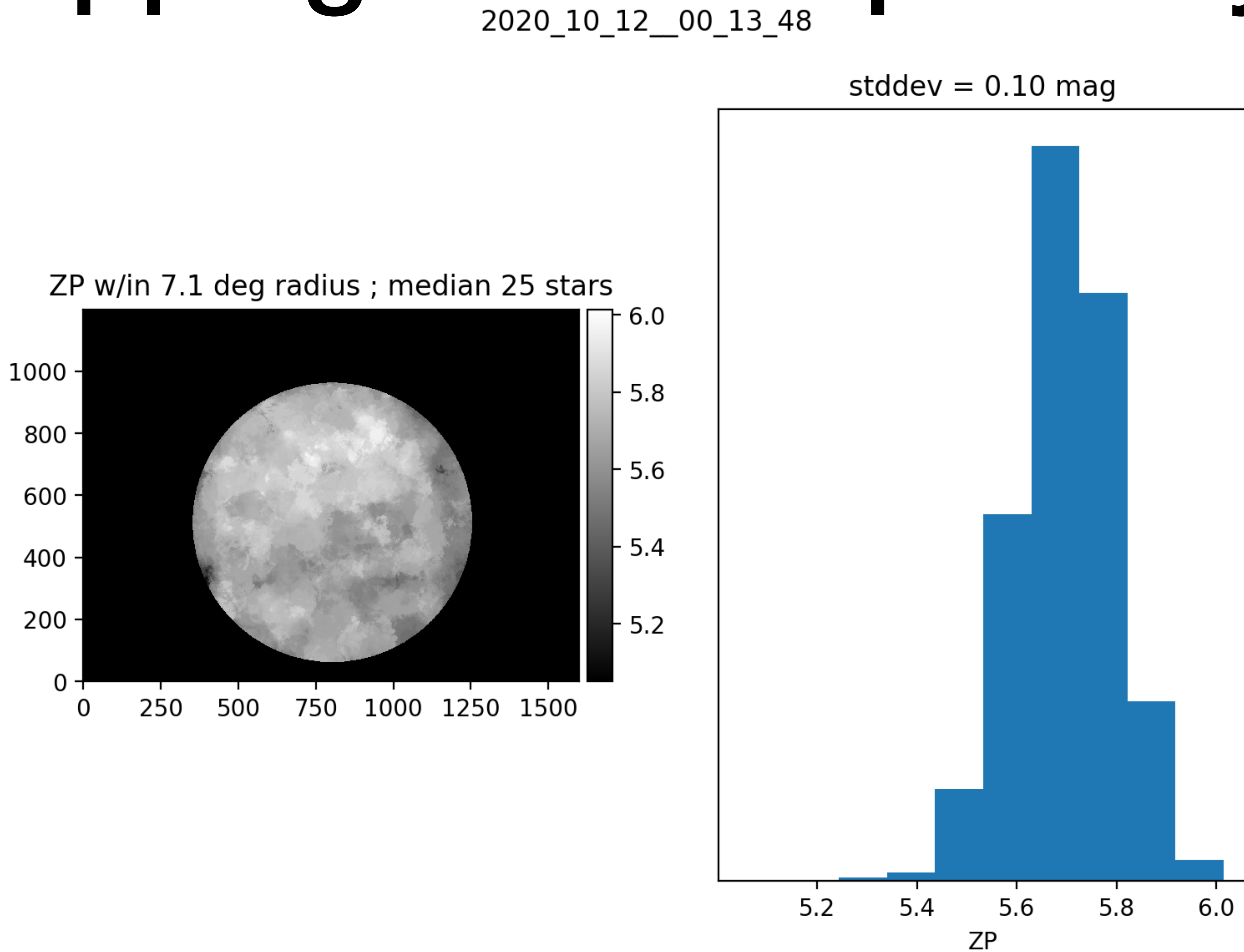

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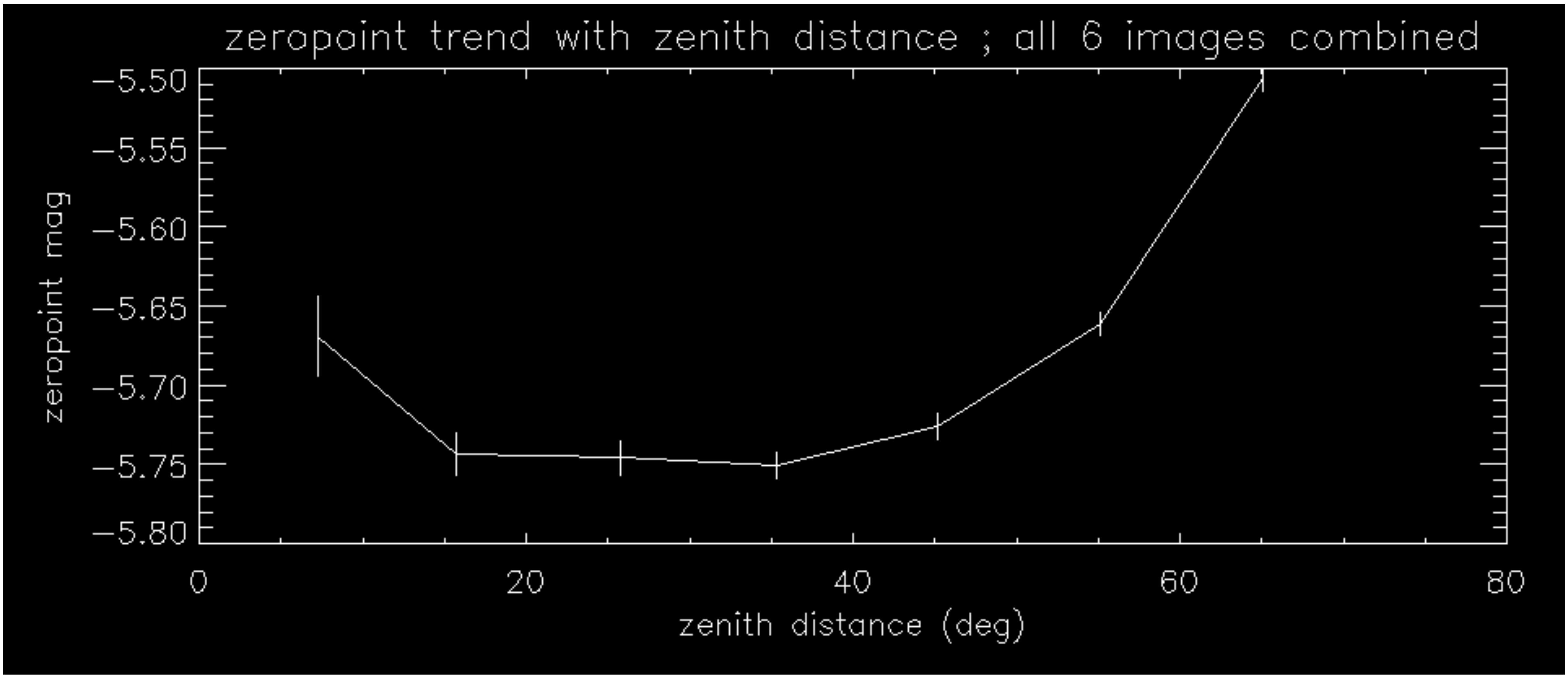
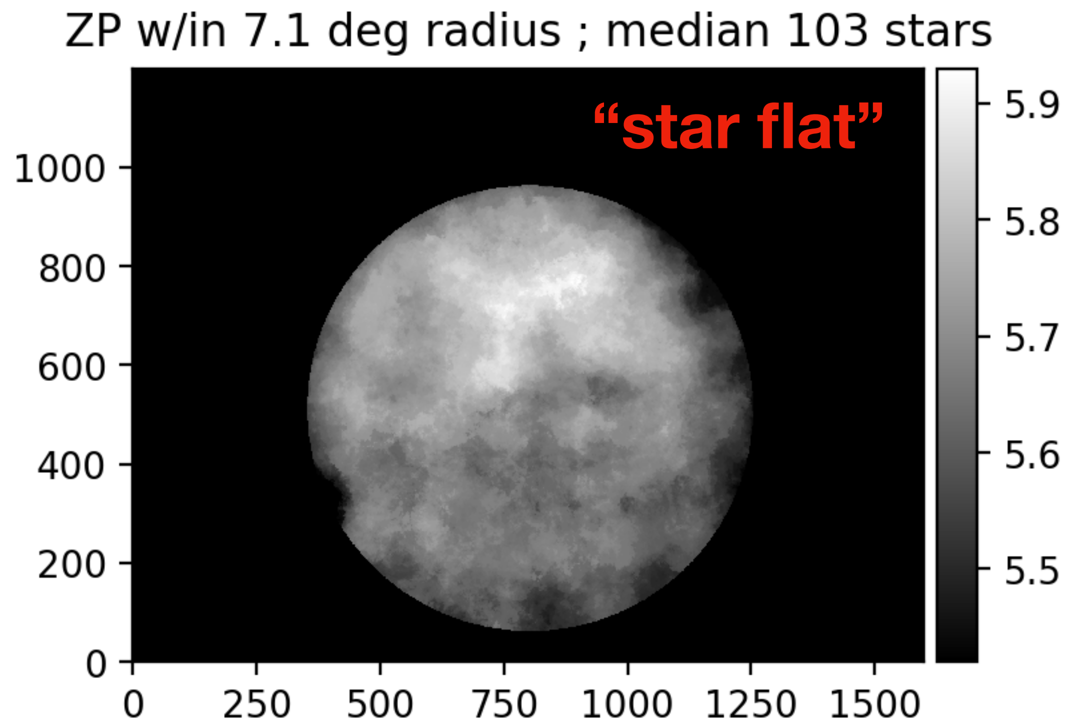
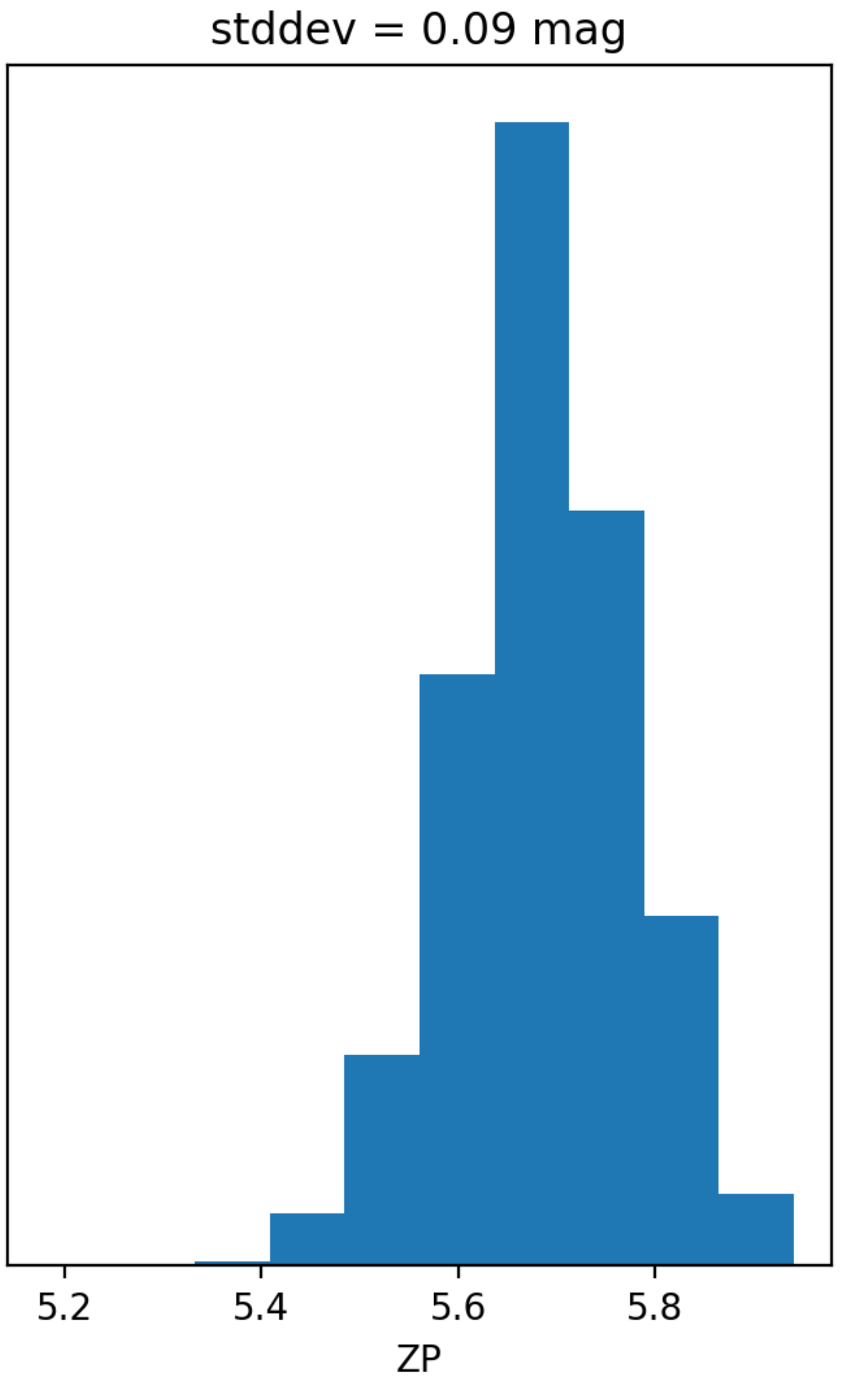
zeropoint trend with altitude?



Creating a “star flat”





- Above is a 2D map of the zeropoint variation lumping stars from all 4 Moon-less exposures together
- After correcting for this 2D “star flat”, the residual RMS in the per-exposure maps binned into patches of 7.1 deg radius is 0.055 mags (versus 0.1-0.11 mags previously, so a ~2x RMS reduction)
- There is some circularity in doing this because the star flat is being used to correct exposures that contributed to the creation of the star flat (which only incorporates a total of four exposures)

Limiting magnitude

- Using a couple dozen moderately bright, unsaturated stars the 1st image (dark sky), I find n_eff = 7.15 pixels
- Given the sky background noise and a zeropoint of V = 5.66, this translates to a 5 sigma brightness of V = 6.54
- This limiting mag value seems reasonable when overplotting the locations of V ~ 6.5 stars on the example dark time MDM all-sky camera images

Limitations

- Only 8 bits of dynamic range in the sample MDM FITS files
- Sample FITS files only span ~8 hours
  - Can’t tell us anything about long-term stability of e.g., gain or trends with environmental conditions
- No dedicated calibration frames
- I’m not sure whether the night of 2020 October 11-12 was truly photometric, although the stability of the all-sky camera zeropoint over 7+ hours suggests that it was
- Eric Galayda notes that the protective dome over the MDM all-sky camera is plastic, not glass, and it may not be entirely clean. This could introduce apparent photometric zeropoint variations across the sky.

Future directions

- Try running this same analysis on the public MDM JPG files?
  - Will need to dodge/mask text annotations…
- Different bright star catalog that goes a bit fainter?
  - Tycho?
  - Match to Gaia for G, BP, RP mags?
- Try to understand bandpass / color corrections
  - Empirical look-up table of each bright star's all-sky camera flux under photometric conditions to eliminate the need for any comparison to external catalogs with differing bandpasses?
- Transparency mapping:
  - Need to understand/decrease the scatter in per-star implied zeropoint, i.e. the scatter in instrumental mags relative to the input bright star catalog
  - Weighting of stars based on S/N (current zeropoint maps just take the median across implied zeropoints of all ~25 stars in each sky patch, most of which are faint)