Venus Transit of 2012 Observed by the Helioseismic and Magnetic Imager (HMI) on board the Solar Dynamics Observatory (SDO)

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PICARD Workshop, September 25-26, 2013

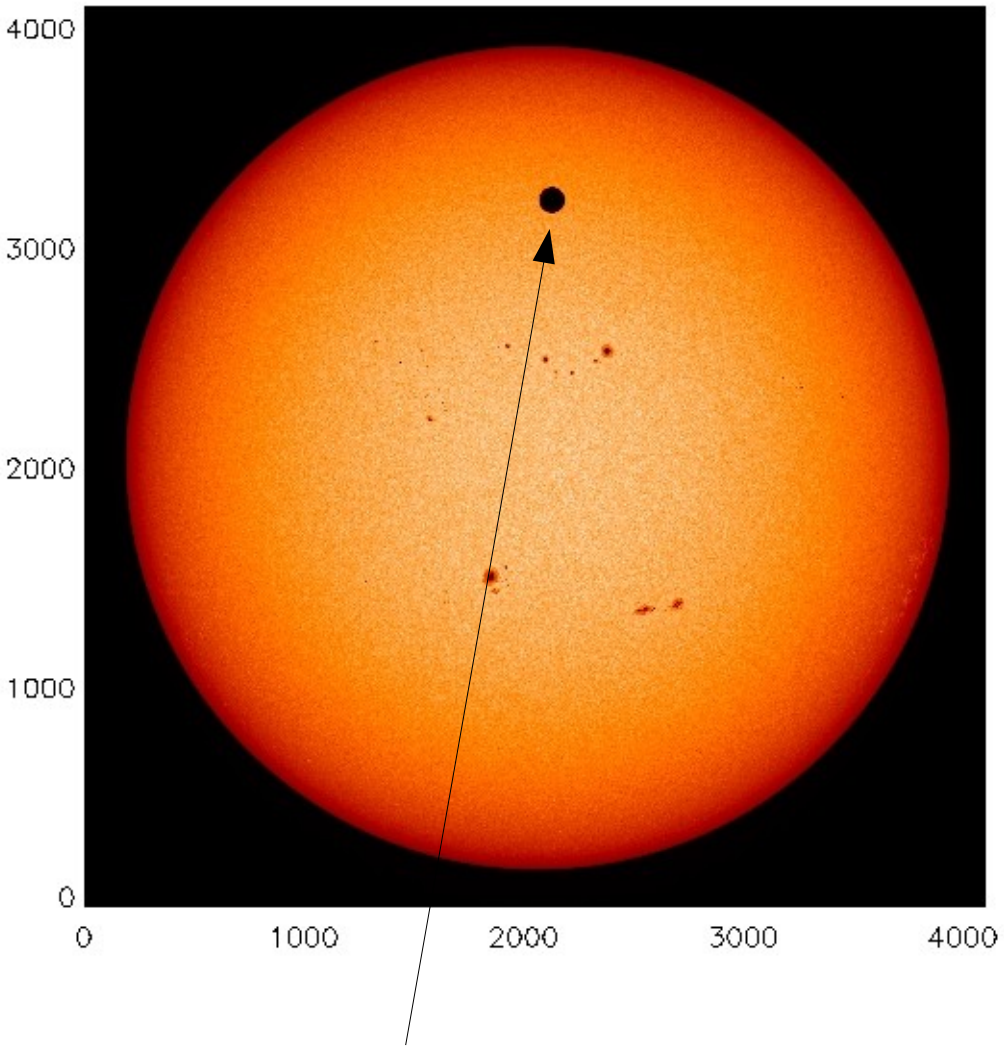
What we learned from the Venus transit of June 5-6, 2012

Rock Bush will present the HMI instrument in details tomorrow
HMI images the Sun onto 4096x4096 CCDs, in Fe I line at 6173 A
Cadence of 45 s on front camera: 6 wavelengths, 2 polarizations
Cadence of 135 s on side camera: 6 wavelengths, 6 polarizations

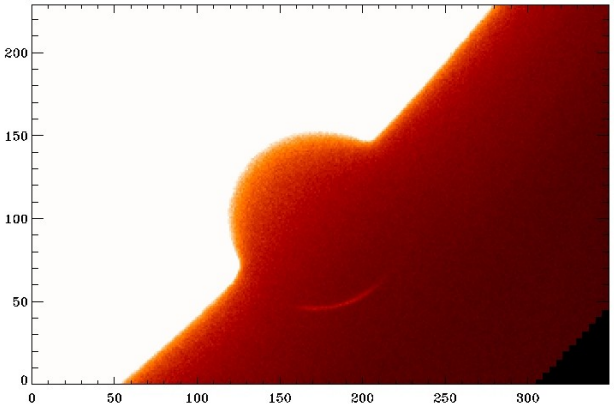
Previous Venus transit was in June 2004, next one is in December 2117
The transit of June 2012 proved very useful to HMI team
To improve the calibration of HMI:
- **roll angle** (satellite + instrument) -> keyword CROTA2
- **plate scale** -> keyword CDELT1
- **Point Spread Function** (PSF)
To test the quality of HMI's ground calibration
- **instrument distortion**
To access science data:
- measurement of the **solar radius** (work in collaboration with Picard team members at LATMOS: Hauchecorne, A., Irbah, A., and Meftah, M.)
- measurement of **linear polarization in Venus atmosphere**

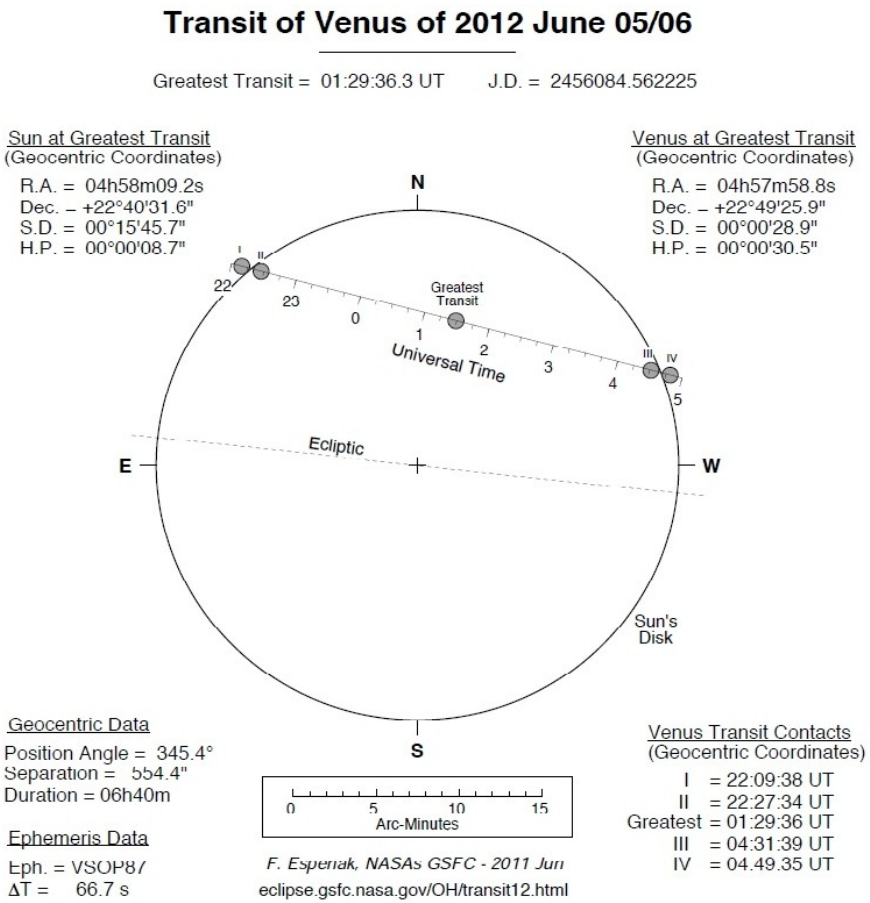
will briefly present some of these results, starting by the measurement of the solar radius

Venus transit of June 5-6, 2012: an overview

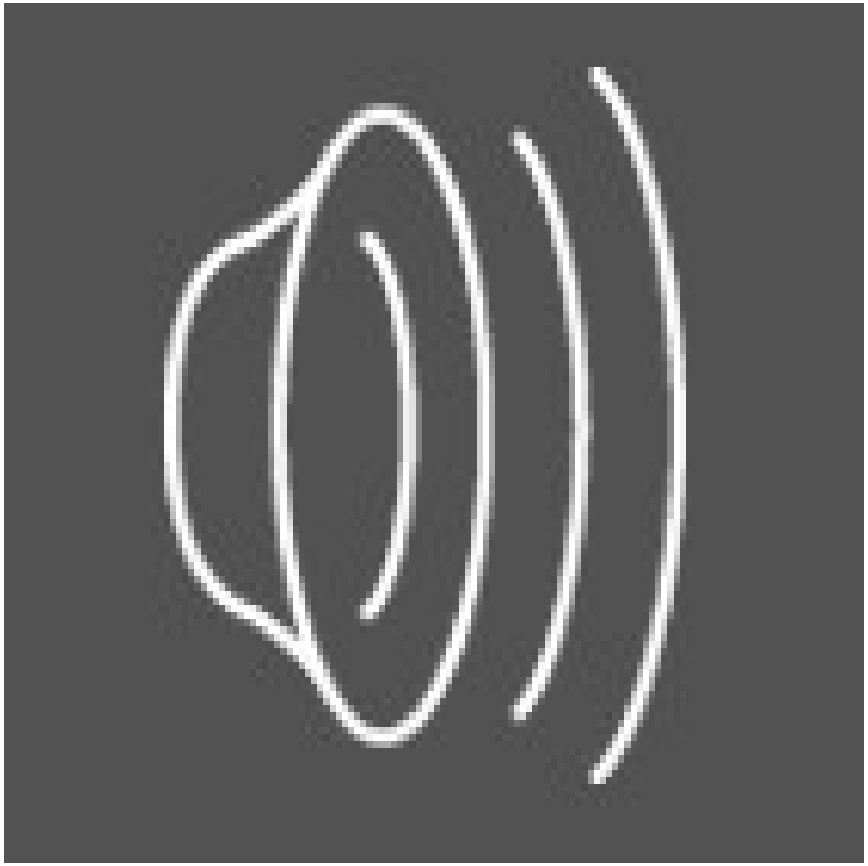


Venus radius = 57.8 pixels



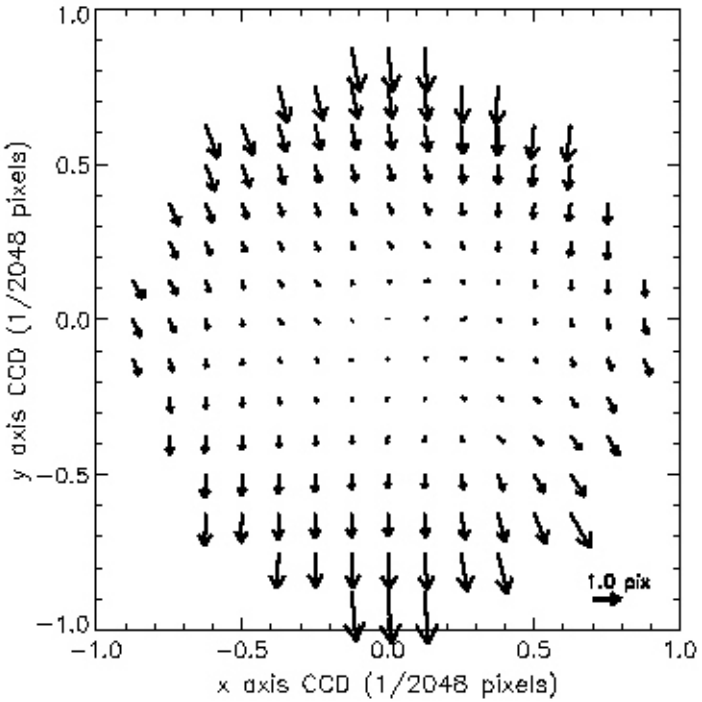


During transit side camera of HMI took true continuum at 4 polarizations (I+U,I-U,I+Q, and I-Q)



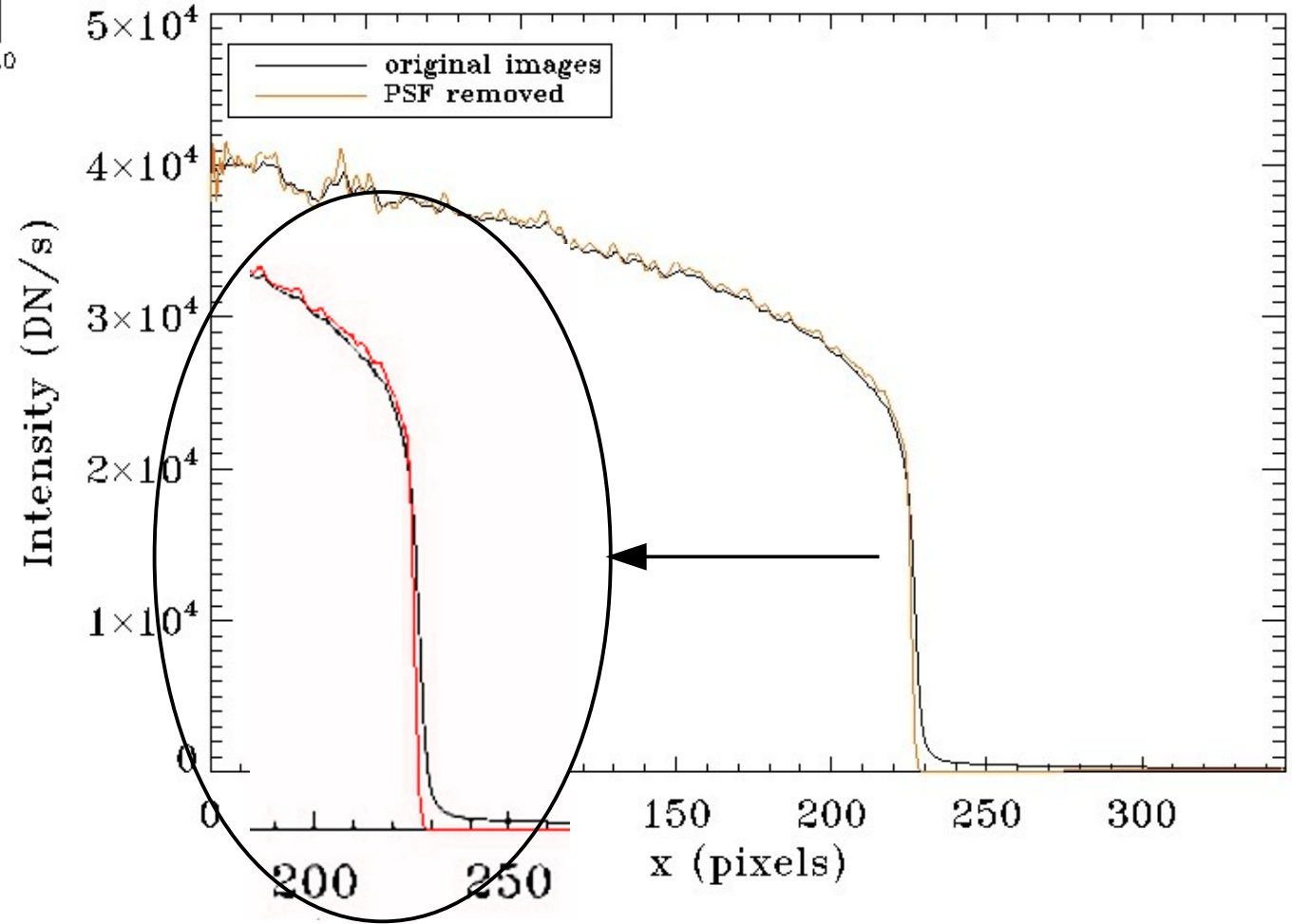
Credit: Data courtesy of NASA/SDO, HMI, and AIA science teams.

Solar Radius Measurement Image Processing (I)



Front camera distortion
From Wachter *et al.*, 2012

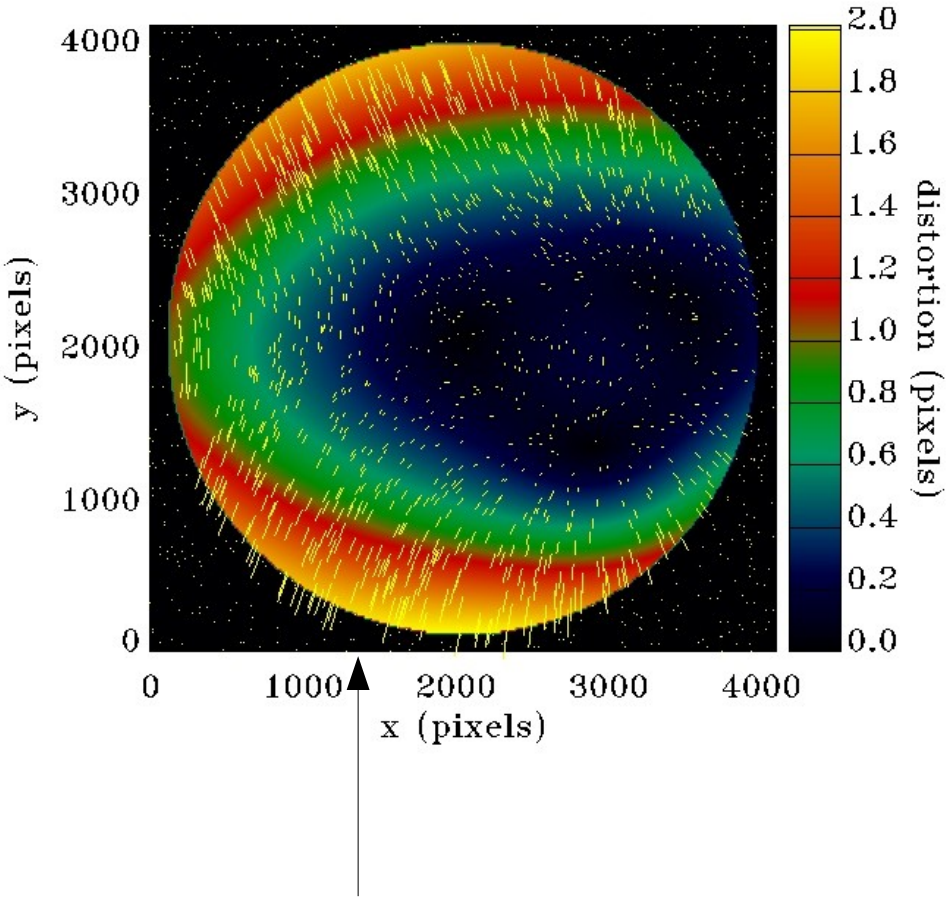
- based on Emilio, Kuhn, Bush, and Scholl (2012)
- using hmi.lev1 data from side camera only: 25 min for ingress and egress
- gap filling of hmi.lev1 (to correct bad pixels)
- un-distortion
- removing PSF (using Richardson-Lucy algorithm). PSF from A.A. Norton, T.L. Duvall, and J. Schou



Side note on HMI distortion

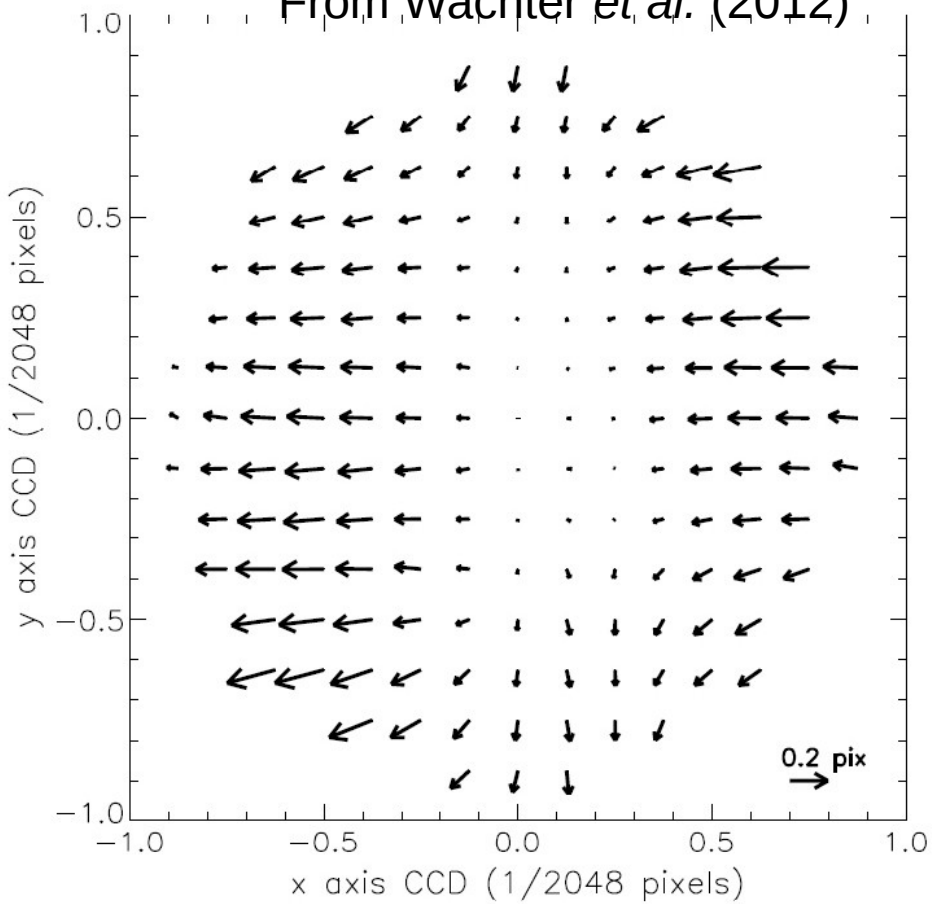
- obtained from ground data (random-dot target + moving alignment legs, Wachter *et al.* 2012)
- distortion as a function of field position is expanded into Zernike polynomials up to 23rd order
- when we correct images for distortion to obtain HMI observables, we use polynomials of order 6 separately for x and y. Distortion is mostly “pincushion” type in upper half, and “barrel” type in lower half (aka “mustache” distortion)
- elliptical distortion could be further corrected using roll data from space

Front camera at best focus:



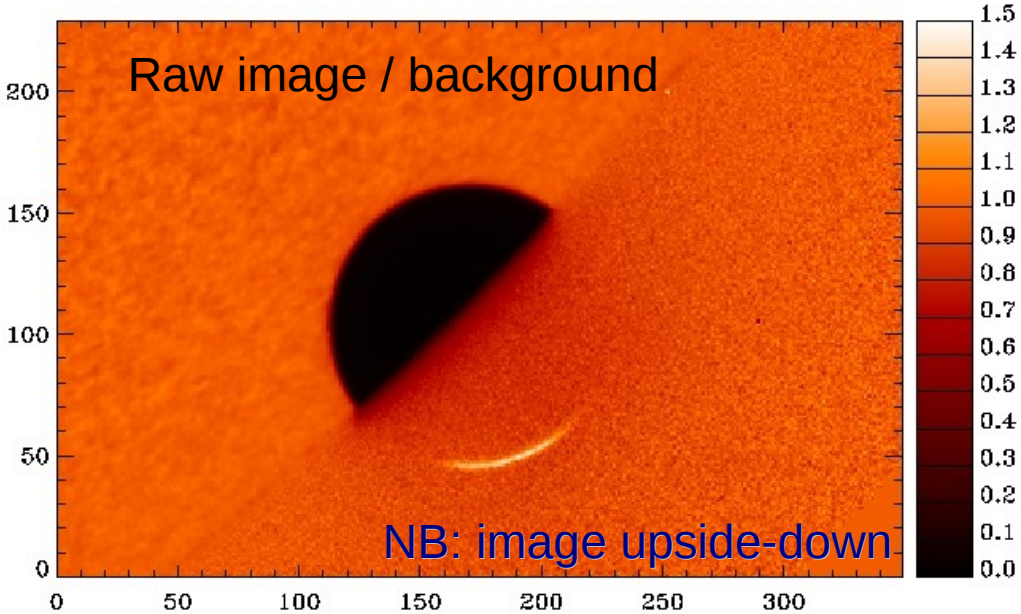
Max distortion: 2 pixels

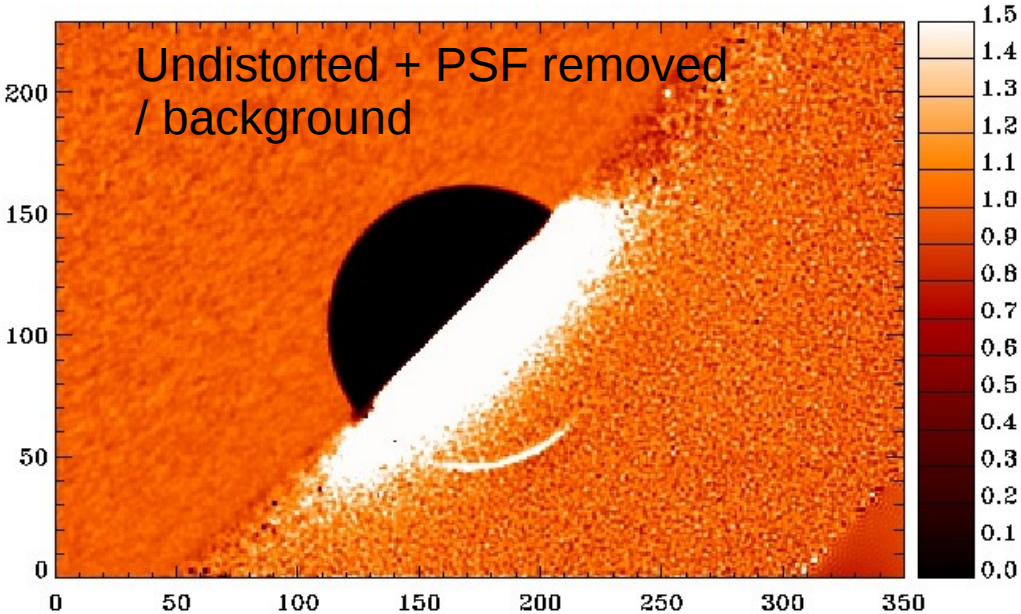
Front – side cameras:
From Wachter *et al.* (2012)



Max difference: 0.28 pixels

Solar radius determination: Image Processing (II)

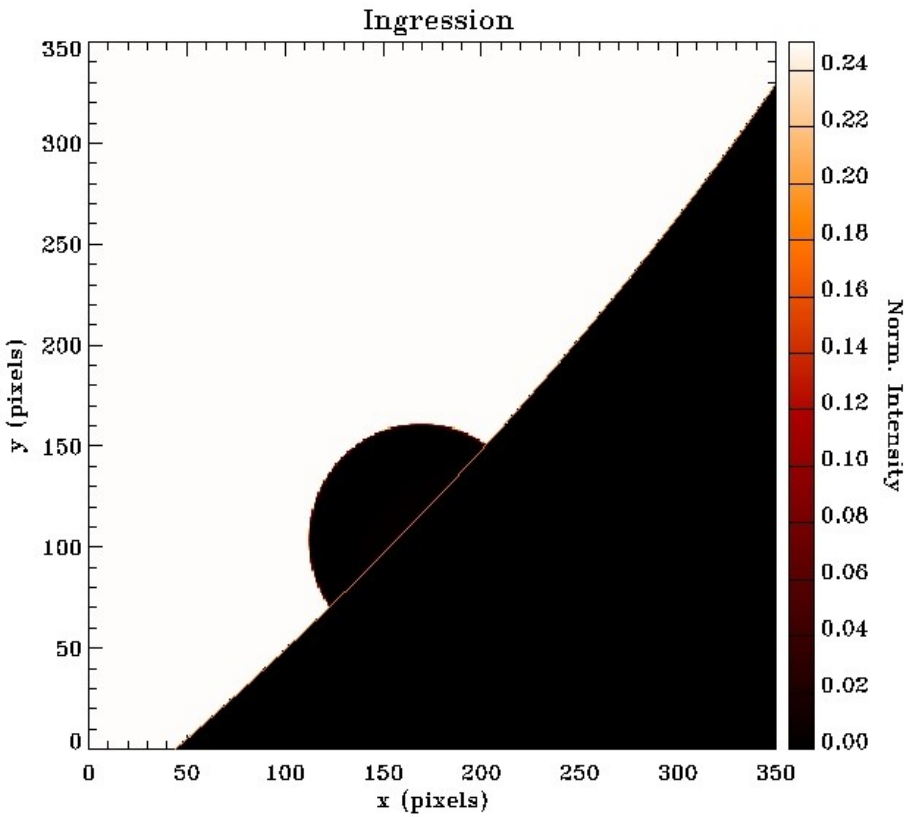




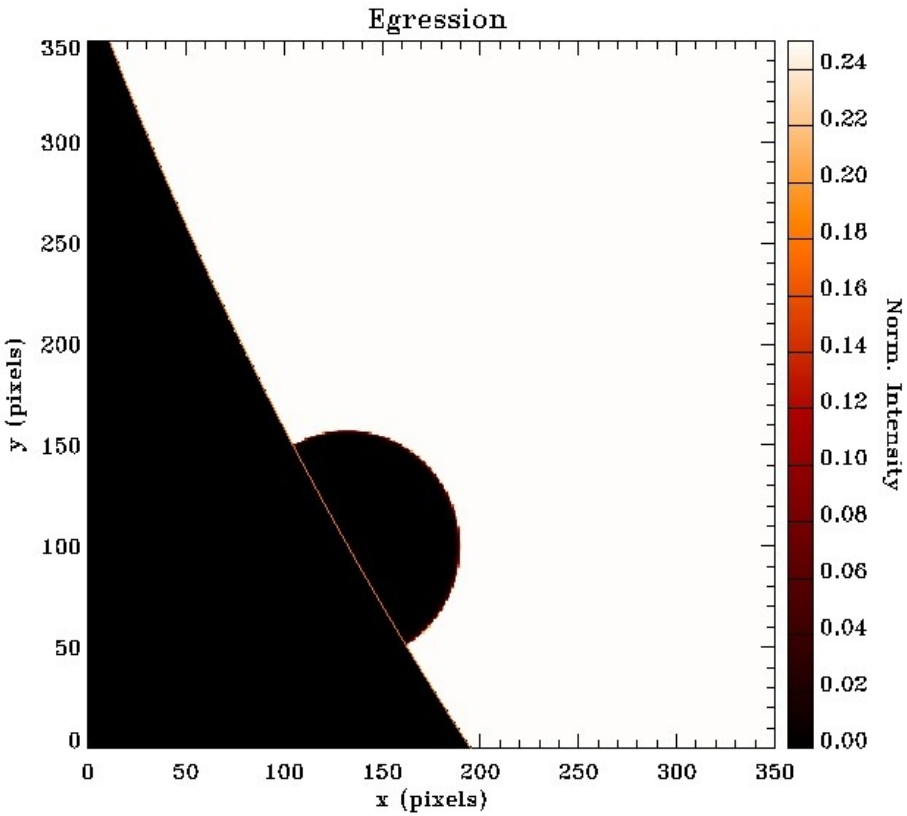
- dividing each image by background images (average from 80 images prior to, and after the, transit, i.e. 5 min)
- finding the limb on each image (limb finder results corrected by un-distortion), and masking
- thresholding and pixel counting (pixels below threshold assumed to be part of Venus)
- determining times at which center of Venus crosses solar radius (NB: contact between center and radius happens when 49.6% of surface area is inside solar disk)

Interpolation on fine time grid

- comparing total transit time with ephemeris provided by GSFC: we determine solar radius which, based on ephemeris, returns closest transit time to observed one

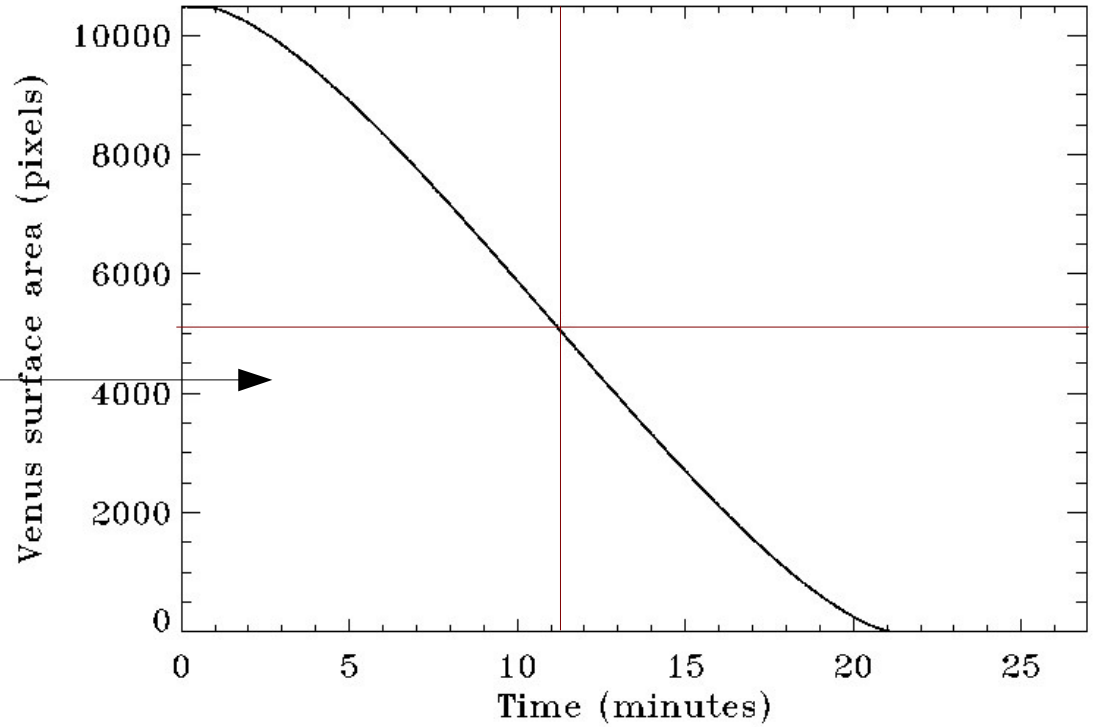


Example of processed images that have been thresholded and masked

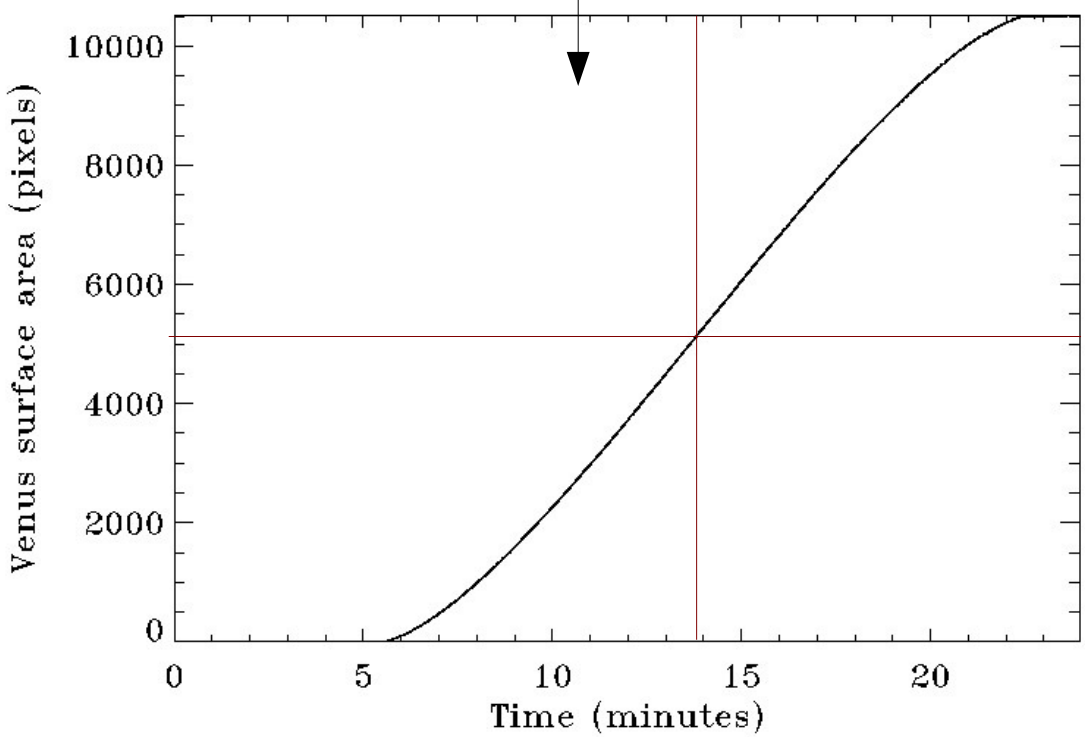


Measuring the surface area of part of Venus inside the solar disk

egression



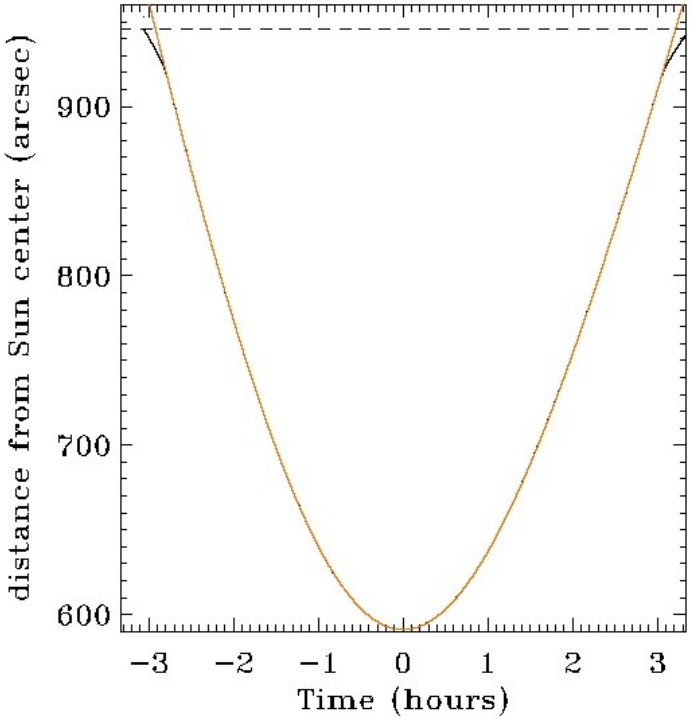
ingression

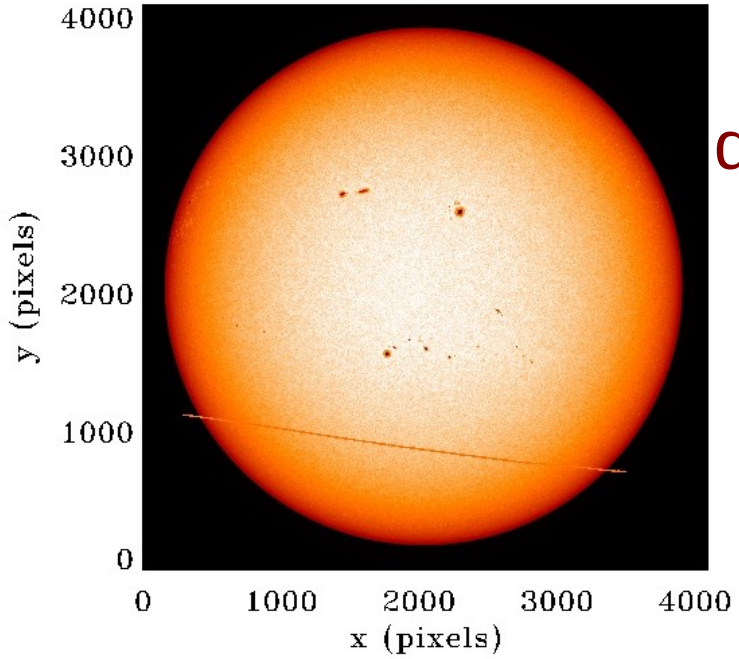


RESULTS:

- total transit time from HMI data:
6h 8m 9s
- compared to ephemeris, corresponds to average radius at 1 AU:
959.7” ± 0.2” (i.e. 145 km at least)
Close to 959.86” from Meftah *et al.* (2013)
Close to the 959.9” measured by Alain Hauchecorne (for HMI)
But: result is sensitive to PSF used and removal details, to threshold used, to limb position...

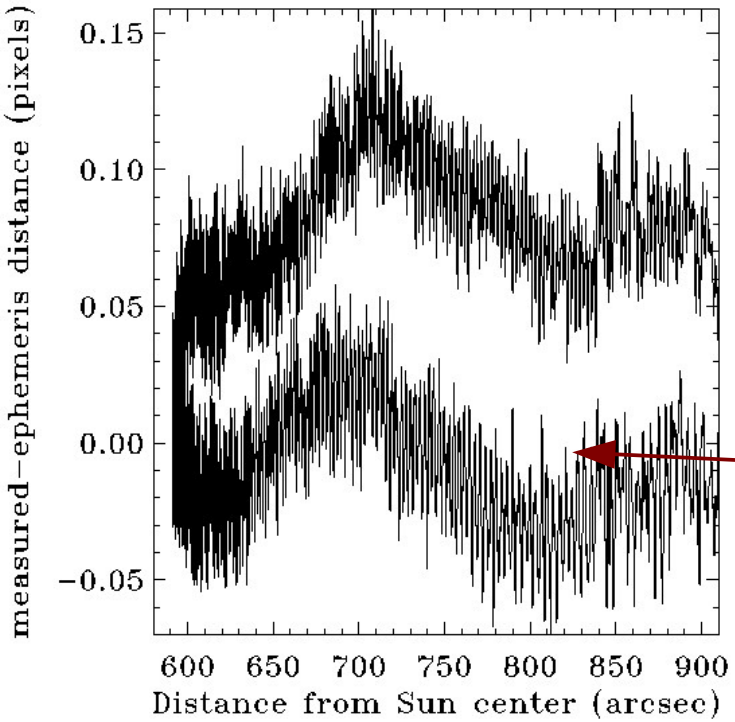
HMI residual distortion along the path of Venus

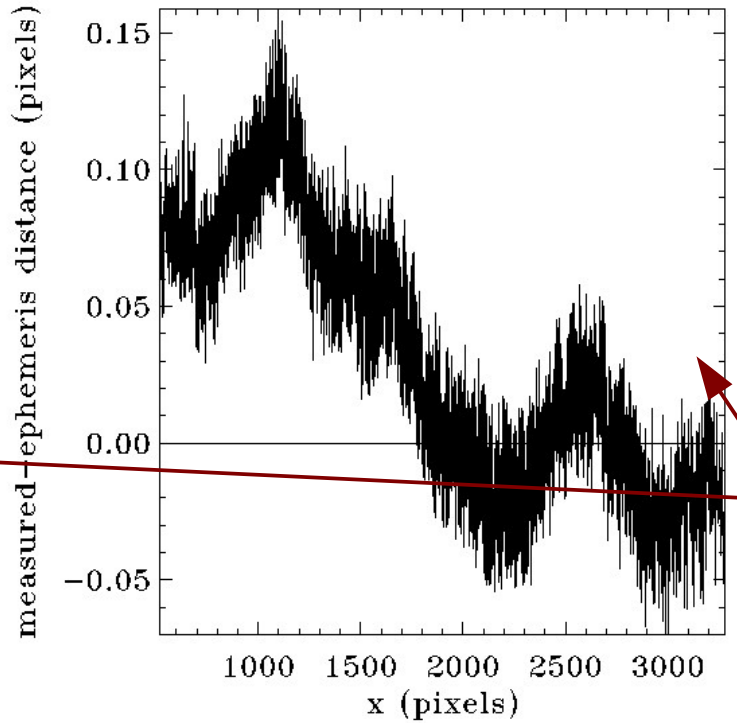




Comparison of Venus center locations with ephemeris locations

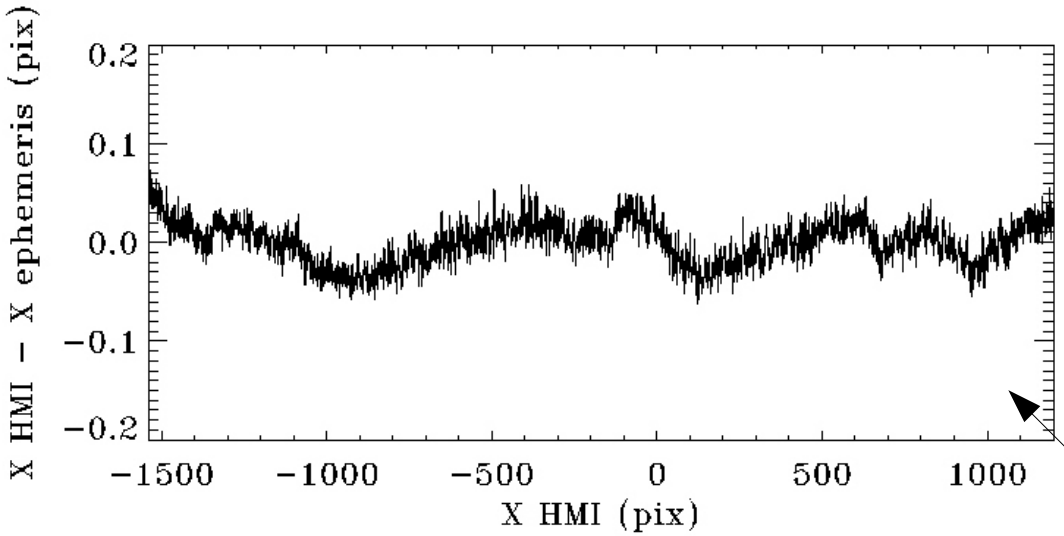
- images are un-distorted
- PSF is removed
- images are divided by background image
- Venus center defined as center of gravity of all pixels below given threshold



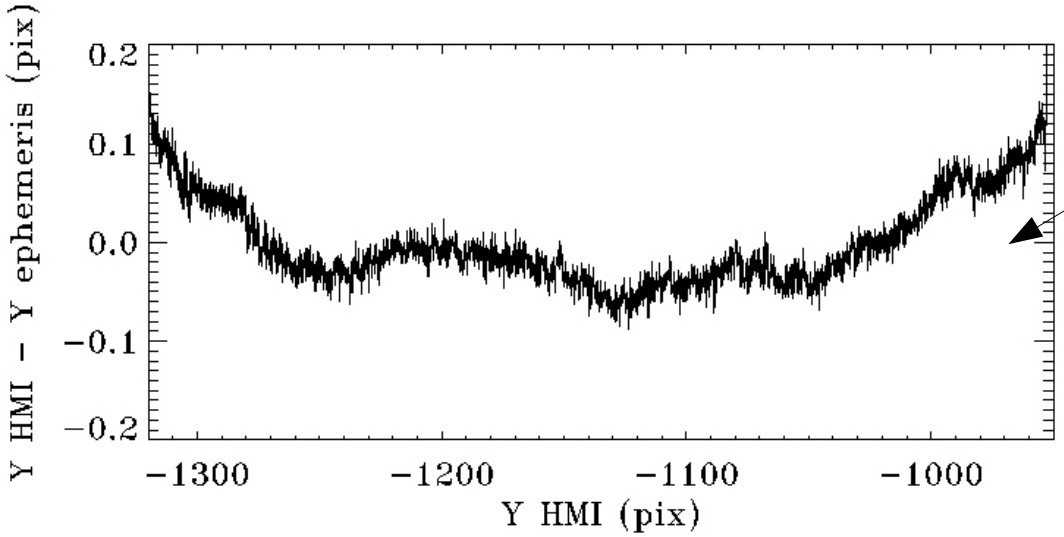


Assuming the plate-scale is correct

Residual distortion in the x and y directions (adapted from J. Schou)



To determine accurate residuals in x and y, it is necessary to also fit for plate-scale (CDELT1) and roll angle (CROTA2). Non-linear LSQ fit using Levenberg-Marquardt algorithm



Residual distortion ≤ 0.1 pixel

Roll Angle of HMI

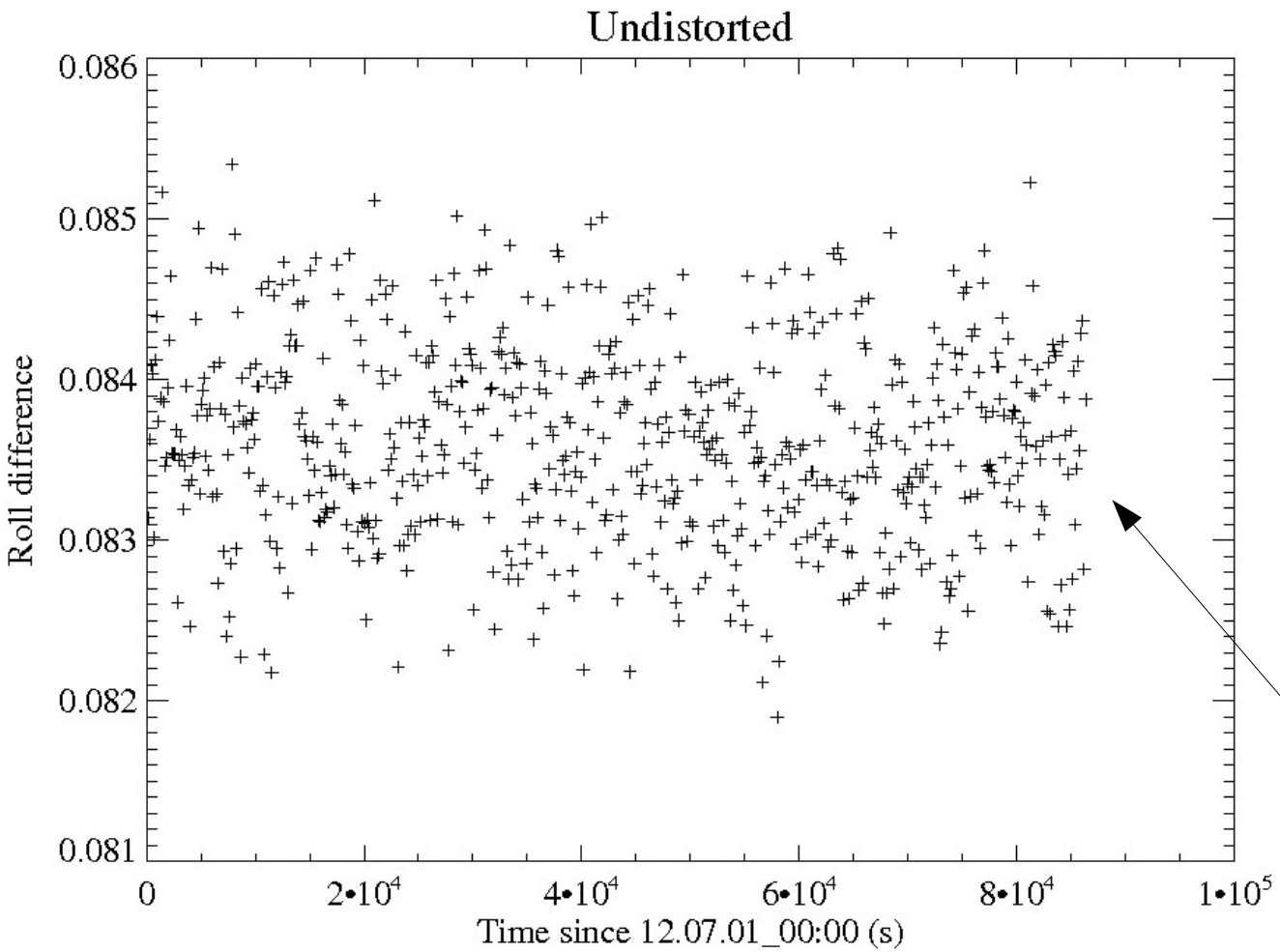


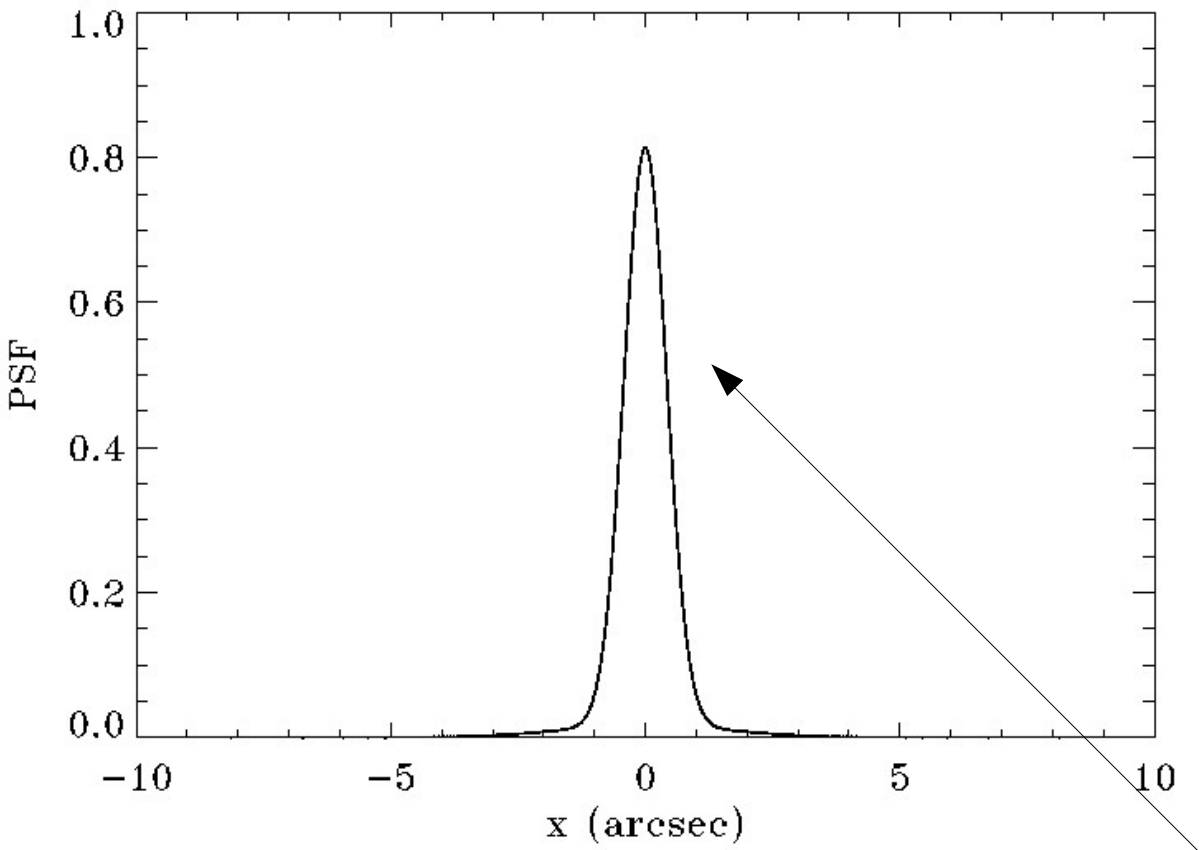
Figure provided by J. Schou

Venus transit data are used to determine error on the CROTA2 keyword (satellite roll angle + instrument roll angle) Analysis from J. Schou and R. Shine based on un-distorted level 1 images

Average angle error: 0.0834°

CROTA2 corrected in all hmi.lev1 records after 2012.08.29

Point Spread Function



From Yeo et al., submitted

Several PSFs have been obtained:

From Venus data

- K.L. Yeo et al. -> 5 Gaussians whose amplitudes have a sine-like azimuthal dependence
- A. Norton, T. L. Duvall, and J. Schou -> Airy function + Lorentzian + minor azimuthal dependence

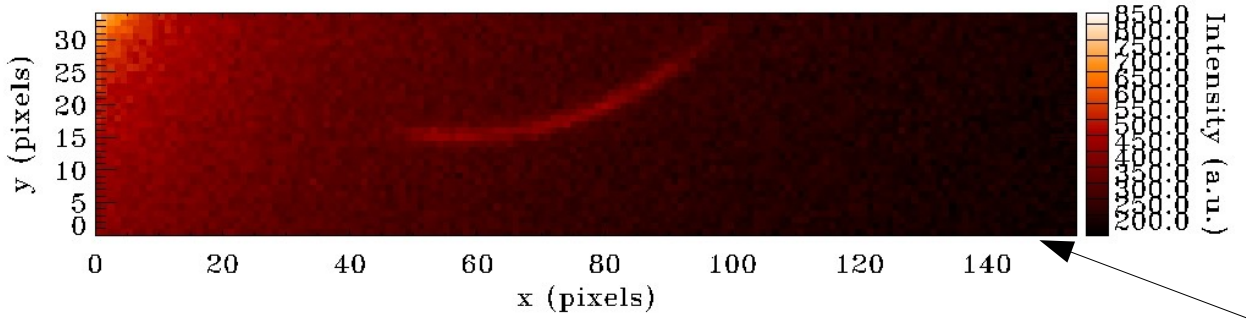
From ground data

- R. Wachter et al. -> 1 Gaussian + tail described as a power drop-off

FWHM=0.96” or 1.9 pixels

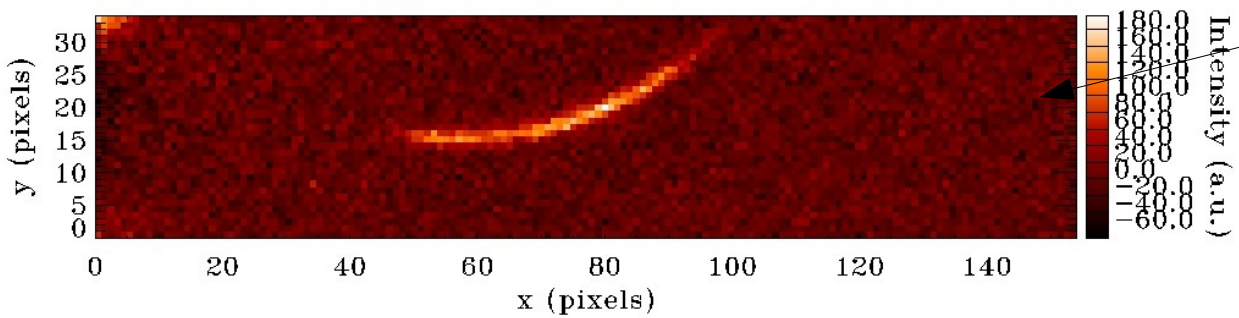
Measurement of Linear Polarization in Venus Atmosphere (work in progress)

- scattering of sunlight by Venus mesosphere expected to produce some amount of linear polarization
- difficult to observe due to phase angle close to 180° + instrument defects & limb polarization
- during Venus transit side camera took I+/-U and I+/-Q in continuum, at cadence of 3.75 s (horizontal linear polarization seen from the instrument is I + Q, while I + U is polarization at 45° counterclockwise from horizontal (Schou et al., 2012))



Venus observed during ingression outside solar disk. Average aureole intensity measured.

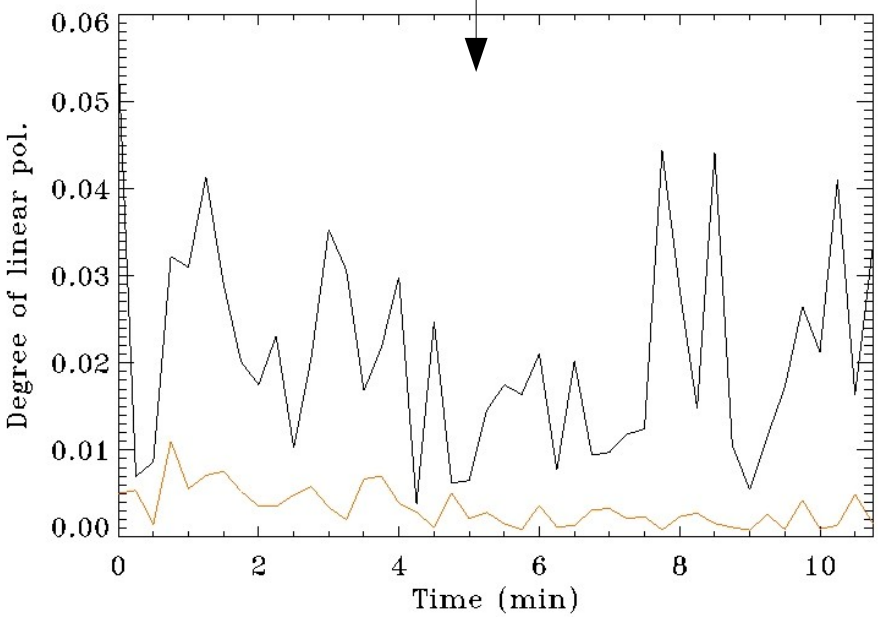
Raw level 1 images

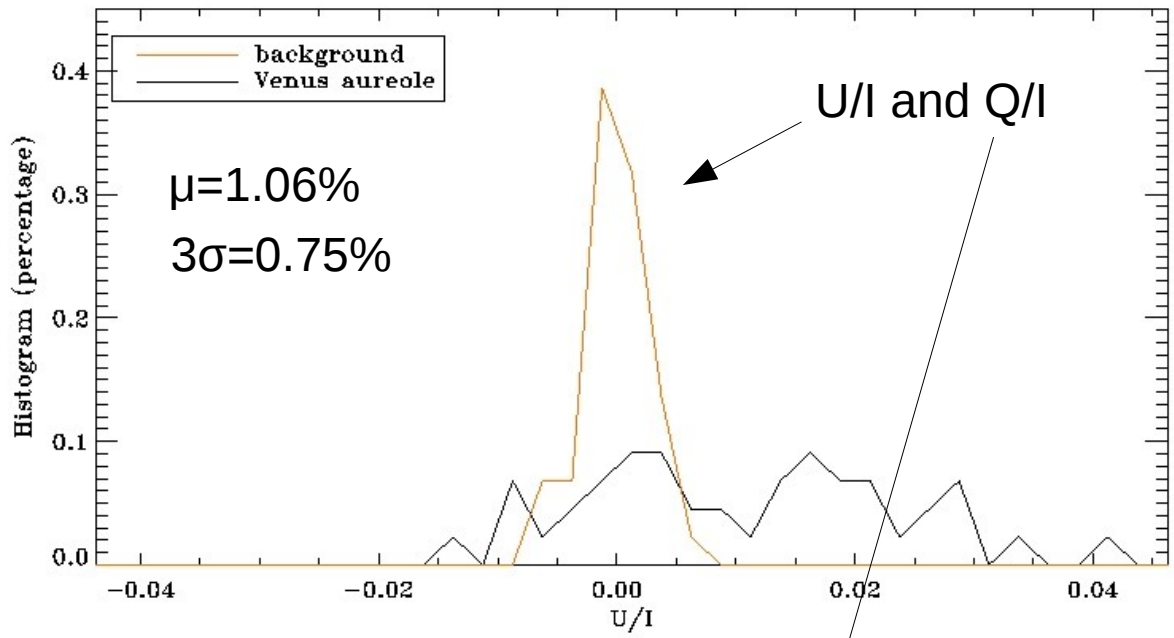


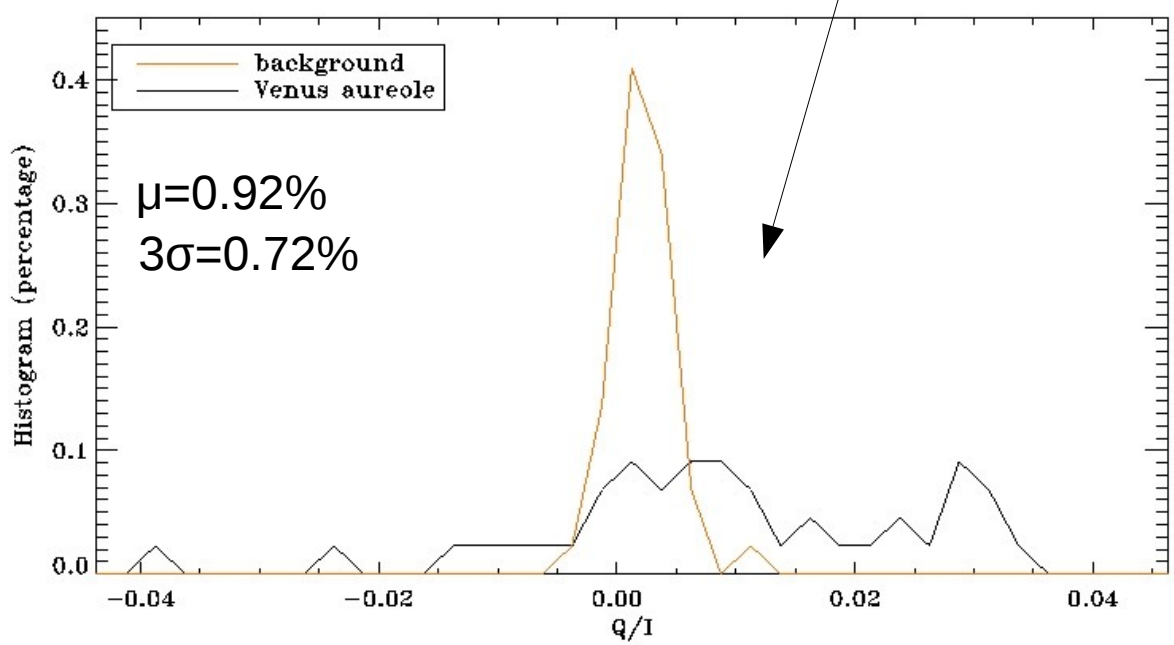
Background removed, cosmic ray hit removed

Result of average linear polarization measurement

Degree of linear polarization $\sqrt{(U^2+Q^2)}/I$
Average = 2.11% (background: average = 0.34% and σ=0.22%)







Conclusion

- Venus transit provided HMI team unique opportunity to better know and improve calibration of instrument (roll angle, plate scale, distortion)
- to measure the solar radius (collaborative work with Picard group)
- to determine PSF (work in progress, papers by A.A. Norton, T.L. Duvall, J. Schou, *et al.* and by K.L. Yeo, A. Feller, S.K. Solanki, *et al.*)
- to measure linear polarization in Venus atmosphere (work in progress)

Hopefully we will observe the May 2016 transit of Mercury!

Many thanks to Alain Hauchecorne, Abdenour Irbah, and Mustapha Meftah for the invitation to the workshop!