Production of the 12-min averaged IQUV observables

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1. Stokes Vector Processing Description

The Stokes-vector observables code produces the 12-min averaged IQUV observables. Each output of the code is computed for a given target time (T_REC). The time step of T_REC is 12 minutes. The code runs on hmi.lev1 records, known as filtergrams, taken by the side camera of HMI. The current observables sequence on this camera takes 6 polarizations and 6 wavelengths at a cadence of 135 s. These level 1 data are level 0 (i.e. raw) filtergrams that have been flat-fielded, have a dark frame subtracted, and have the overscan rows and columns of the CCD removed. Moreover a limb fitting code was run to obtain, among others, the solar disk center coordinates on the CCD and the observed solar radius. A list of bad (either permanently or temporarily) pixels is stored in the bad_pixel_list segment of each hmi.lev1 record. The keywords CRPIX1 and CRPIX2 (disk center location), CDELT1 (image scale), and RSUN_OBS (solar radius at the SDO distance) returned by the limb finder are corrected for the differences in atmospheric height sampled by the wavelength at which the filtergram was taken. This correction was initially implemented in the observables code but has since been moved to level 1. The flat field used is the so-called PZT flat field, which is updated once a week. Due to these regular updates, observables calculated for T_REC close to midnight TAI may be obtained partly from level 1 filtergrams using the flat field of the previous 24 h, and partly from filtergrams using the flat field of the next 24 h. Flat fields are stored in the hmi.flatfield series. PZT flat fields are obtained by offsetting the HMI field of view (FOV) with the piezo-electric transductors (Wachter and Schou, 2009). In a near future, we plan to use rotational flat fields instead, based on the rotation of the solar disk to offset the FOV. When implemented, these flat fields will be applied in the observables code itself. The rotational flat fields are stored in the series hmi.flafield_update. The use of rotational flat fields instead of PZT ones will be a command-line option of the observables code. If this option is selected, the observables code will retrieve the appropriate PZT flat field(s), remove them from the level 1 records, and then apply the rotational flat field(s).

After reading the appropriate keywords and data segments of the level 1 records, and after taking care of the flat field (if needed), the main program calls the gap filling routine on each filtergram read. The list of bad pixels that need to be corrected is sent to the routine with the filtergram itself, and this routine tries to spatially interpolate over these missing/bad pixels. A list of cosmic-ray hits (one per filtergram) is also read in the series hmi.cosmic_rays, and the pixels in this list are provided to the gap filling function. It returns the corrected filtergram and an array containing information regarding the successful, or not, completion of the gapfilling.

The observables code then gives the hand to a temporal averaging routine that performs:

- de-rotation: each filtergram is re-registered to correct for the pixel shift incurred by solar structures as a result of solar rotation. This correction is done at sub-pixel accuracy using a Wiener spatial-interpolation scheme. The time difference used to calculate the pixel shift for a given level 1 filtergram is T_REC-T_OBS, where T_OBS is the observation time of the filtergram;

- un-distortion: each filtergram is re-registered to correct for intrumental distortion;

- centering: each filtergram is spatially interpolated to a common solar disk center that is an average (CRPIX1,CPRIX2) from the filtergrams used to produce the IQUV observables at T_REC.

- temporal averaging: de-rotated, re-centered, and un-distorted filtergrams are averaged together to the target time T_REC.

The differential solar-rotation profile used for the de-rotation correction is stored in the file rotcoef_file.txt. The instrumental distortion as a function of field position has been expanded into Zernike polynomials, whose coefficients are stored in the text files distmodel_front_o6_100624.txt for the front camera, and distmodel_side_o6_100624.txt for the side one. The solar disk center and radius of the undistorted images are calculated inside the un-distortion function, and returned as outputs. The temporal averaging is performed in two steps: first an temporal interpolation onto a regular temporal grid with a cadence of 45 s, followed by the actual averaging over 720 s. The time window over which the temporal interpolation is performed is 1215 s, which is wider than the time window of 720 s over which the temporal averaging is later performed: a wider window is required as the temporal interpolation needs several filtergrams before and after the interpolation times. Finally, the temporal averaging routine also returns a mask with some error estimates that can be used to decide whether or not to accept the processed image (a feature currently not used).

Then, the observables code calls the polarization calibration routine, which converts the 6 polarizations taken by the observables sequence into a Stokes vector (I, Q, U, V). To perform this conversion, the polarimetric model described in Schou et al. (2011) is used, including the corrections based on the front window temperature (based on the average of sensors TS01 and TS02) and the polarization selector temperature (TS08). These temperatures are fetched in the series hmi.temperature_summary_300s. At each point in the image a least squares inversion is then performed to derive (I, Q, U, V) from the six polarization states observed.

Two additional corrections are applied to the model described in Schou (2011). The first is to add what appears as a telescope polarization term, in other words a term proportional to I is added to the demodulated Q and U (the effect on V is negligible, so no correction is made). The coefficients of proportionality are given as fourth order polynomials in the distance from the center of the image. It may be noted that this is not actually a telescope polarization term as it is observed to vary with polarization selector settings.

While the need for the first correction was expected, the second one was unexpected. What is seen is what appears to be a large (relative to the photon noise) granulation like signal in Q and U (again, V is largely unaffected). Upon further inspection this signal appears to be caused by a different PSF for different polarizations, resulting in I convolved with a PSF difference being added to to linear polarization signal. This is corrected by convolving I with a five by five kernel and subtracting the result. At present a spatially independent kernel is used.

The final results of the Stokes-vector observables code are the Stokes parameters at the 6 wavelengths, that are saved in the series hmi.S_720s.

Finally, the line-of-sight (LOS) observables code is called, to compute the Doppler velocity, LOS magnetic-field strength, Fe I linewidth, linedepth, and continuum intensity, from the Stokes parameters at the specific target time T_REC requested. These LOS observables are calculated with the MDI-like algorithm, detailed in Couvidat et al. (2011). Briefly, discrete estimates of the first and second Fourier coefficients of the solar neutral iron line are calculated from the 6 HMI intensities (wavelengths), separately for the I+V and I−V polarizations. The Doppler velocities are proportional to the phase of the Fourier coefficients (currently, only the first Fourier coefficients are used to compute the velocity). However, the HMI filter profiles are not delta functions, the discrete estimate to the Fourier coefficients is not reliable due to the small number of wavelength samples, and the Fe I line profile is not Gaussian (an assumption used to relate the phase to the velocity). Hence the need to correct Doppler velocities returned by the algorithm. This is achieved in two steps. The first one relies on look-up tables: tabulated functions saved in the hmi.lookup series and computed by a separate code. These tables are computed based on calibrated HMI filter transmission profiles, and on a realistic Fe I line profile. They vary slightly across the HMI CCDs, and with time (due, mainly, to the drift in the Michelson interferometers). They also depend on the tuning of the instrument, and must be re-calculated at each HMI re-tuning. However, there are some errors on the filter transmission profiles, and consequently the look-up tables do not manage to completely correct the Doppler velocities. Also, a second correction step has been implemented. Every day, the relationship between the median Doppler velocity (over 99% of the solar disk) minus the Sun-SDO radial velocity (OBS_VR) is fitted as a function of OBS_VR by a 3rd-order polynomial. A temporal interpolation of the closest polynomials in time to T_REC is used to further correct the Doppler velocities. The LOS magnetic-field strength is proportional to the difference between the I+V and I−V (corrected) Doppler velocities. Only Doppler velocities and field strengths are corrected: no correction algorithm was implemented for the other LOS observables. These observables are saved in the following series: hmi.V_720s (Dopplergram), hmi.M_720s (magnetogram), hmi.Ic_720s (continuum intensity), hmi.Lw_720s (linewidth), and hmi.Ld_720s (linedepth).