HMI Synoptic Maps Produced by NSO/NISP

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Abstract

Recently, the National Solar Observatory (NSO) Solar-atmosphere Pipeline Working Group (PWG) has undertaken the production of synoptic maps from Helioseismic and Magnetic Imager (HMI) magnetograms. A set of maps has been processed spanning the data available for 2010-2015 using twice daily images (taken at UT midnight and noon) and running them through the same algorithms used to produce SOLIS/VSM 6302Å mean-magnetic and spatial-variance maps. The contents of this document provide an overview of what these maps look like, and the processing steps used to generate them from the original HMI input data.
1 Basic Product: Integral Carrington Maps

The goal of this project has been to create a series of integral magnetic synoptic maps using HMI data (Schou, et al., 2012) and run using the same algorithms as those that produce the spatial-variance synoptic maps outlined in Bertello, et al. (2014) and derived from NSO SOLIS (Synoptic Optical Long-term Investigations of the Sun) VSM (Vector Spectromagnetograph) 630.2 nm data.

The HMI synoptic maps that we have produced are all integral synoptic maps (spanning 0-360° of a single Carrington rotation), in Carrington-longitude–by–sine(latitude) binning, and in NSO-low-resolution format (360x180 map bins, where contributing observations are weighted by \(\cos^4(\Delta\text{longitude})\) relative to the observed longitude of central meridian).

Unlike the SOLIS/VSM spatial-variance maps produced to date, the HMI synoptic maps have been run using both longitudinal- and vector-observed magnetograms, where the final data-products for each are detailed in §1.1 and §1.2 below. At a minimum, each FITS-file map set includes a frame for:
- the mean photospheric radial magnetic flux,
- the spatial variance of the mean photospheric radial magnetic flux,
- the sum-of-weights from all observations contributing to a given map set.

1.1 Pseudo-radial Maps from LOS Data

For the HMI-longitudinal synoptic maps, we have used data from the HMI m.720s series (longitudinal magnetograms covering a 12-minute integration window, Scherrer, et al. (2012)). In order to produce maps of radial magnetic flux, we have projected the line-of-sight flux values into pseudo-radial values using the assumption of a perfectly radial magnetic field at the photosphere:

\[
B_{r,\text{pseudo}} = \frac{B_{\text{LOS}}}{\cos (\rho)},
\]

where \(B_{\text{LOS}}\) is the observed LOS flux, and \(\rho\) is the center-to-limb (or heliocentric) angle between the line-of-sight vector and the local vertical.

Additionally, with the reasonable levels of quiet-sun sensitivity provided by longitudinal observations, basic methods for filling in unobservable or poorly observed polar fields become viable.
Therefore, for the HMI-LOS derived maps, we have provided a pole-filled version of the mean–pseudo-radial–flux map as an additional frame. Some methods of pole-filling interpolate spatially and temporally across the pole from well-observed dates/latitudes (Sun, et al., 2011). In our case, the polar fields are filled in using a cubic-polynomial surface fit to the currently observed fields at neighboring latitudes. The fit is performed on a polar-projection of the map using low standard-deviation-to-fit measurements only, and the high-latitude fit is then integrated into the observed synoptic map, weighting toward the pole.

A set of example maps derived from HMI-longitudinal magnetograms is shown in Figure 1, while the file-name structure that we have used and the specifics of the FITS-file frame contents are outlined below.

**Filename Structure:**

`xbx73YYMMDDtHHMMcCCCC_000_int-err_dim-180_source-SDO-HMI.fits.gz`

- ‘xbx73’: This is the product code that denotes HMI synoptic maps derived from photospheric longitudinal magnetograms.

- ‘YYMMDDtHHMM’: This is the time-stamp assigned to the map. For Integral synoptic maps, NSO uses the date and time corresponding to the midpoint of a given Carrington rotation.

- ‘cCCCC_000’: This denotes the Carrington rotation mapped as well as the Carrington longitude at the left map edge. As Integral synoptic maps always run from 0 to 360 degrees, the filenames for these maps will always have ‘.000’ for the longitude.
FITS-frame Contents:

| frame | units | title / description |
|-------|-------|---------------------|
| 1     | Gauss | **Weighted-mean Radial Flux Density:**  
The mean value of the radially-projected HMI-LOS magnetograms for each longitude-sine(latitude) map bin. Each input observation is spatially weighted to emphasize contributions observed near the central meridian. |
| 2     | Gauss | **Spatial RMS Estimate:**  
The weighted statistical variance of all radially-projected HMI-LOS-magnetogram-values contributing to a given longitude-sine(latitude) bin (corresponding to the mean-flux values in Frame 1). |
| 3     | counts | **Sum-of-Weights:**  
The sum of weights into each map bin. This includes both the \(\Delta \text{longitude–versus–central-meridian} \) weighting applied across each input observation, as well as the count of sky-image pixels contributing to each observed longitude-sine(latitude) bin. |
| 4     | Gauss | **Pole-filled Mean Radial Flux Density:**  
The pole-filled version of Frame 1. |

1.2 3-Component Maps from Vector Data

For the HMI-vector synoptic maps, we have used data from the HMI b,720s series (fully disambiguated vector magnetograms, [Hoeksema, et al. (2014)], choosing to apply the results of the Radial-accurate disambiguation for the regions of quiet sun ([Metcalf, et al. 2006] [Leka, et al. 2009]). As this is vector data, the mean-radial-flux map in these files is for true-radial flux. Additionally, we have mapped the values for the mean poloidal and toroidal fluxes, and computed the spatial-variance of these quantities. For these additional-component maps, we have used the same cosine\(^4(\Delta \text{longitude}) \) weighting that broadly emphasizes fluxes observed near central meridian.

A set of example maps derived from the HMI-vector magnetograms is shown in Figure 2 while the file-name structure that we have used and the specifics of the FITS-file frame contents are outlined below.

Filename Structure:
`xbx93YYMMDDHHMMcCCCC_000_int-err_dim-180_source-SDO-HMI.fits.gz`

- ‘xbx93’: This is the product code that denotes HMI synoptic maps derived from photospheric vector magnetograms.
- ‘YYMMDDHHMM’: As in §1.1 this is the time-stamp assigned to the map.
- ‘cCCCC_000’: As in §1.1 this denotes the Carrington rotation mapped as well as the Carrington longitude at the left map edge.
Figure 2: Set of example image frames for an HMI-Vector-derived synoptic map: Carrington rotation 2145, centered on April 1st, 2014.
FITS-frame Contents:

| frame | units | title / description |
|-------|-------|---------------------|
| 1     | Gauss | Weighted-mean Radial Flux Density:  
The mean value of the radial (outward) flux (measured from HMI vector magnetograms) for each longitude-sine(latitude) bin. Each input observation is spatially weighted to emphasize contributions observed near the central meridian. |
| 2     | Gauss | Weighted-mean Poloidal Flux Density:  
The mean value of the poloidal (southward) flux (measured from HMI vector magnetograms) for each longitude-sine(latitude) bin. Each input observation is spatially weighted to emphasize contributions observed near the central meridian. |
| 3     | Gauss | Weighted-mean Toroidal Flux Density:  
The mean value of the toroidal (+longitude-ward) flux (measured from HMI vector magnetograms) for each longitude-sine(latitude) bin. Each input observation is spatially weighted to emphasize contributions observed near the central meridian. |
| 4     | Gauss | Radial-flux Spatial RMS Estimate:  
The weighted statistical variance of all HMI-vector radial-flux magnetogram-values contributing to a given longitude-sine(latitude) bin (corresponding to the mean-flux values in Frame 1). |
| 5     | Gauss | Poloidal-flux Spatial RMS Estimate:  
The weighted statistical variance of all HMI-vector poloidal-flux magnetogram-values contributing to a given longitude-sine(latitude) bin (corresponding to the mean-flux values in Frame 2). |
| 6     | Gauss | Toroidal-flux Spatial RMS Estimate:  
The weighted statistical variance of all HMI-vector toroidal-flux magnetogram-values contributing to a given longitude-sine(latitude) bin (corresponding to the mean-flux values in Frame 3). |
| 7     | counts | Sum-of-Weights:  
The sum of weights into each map bin. This includes both the Δlongitude-versus-central-meridian weighting applied across each input observation, as well as the count of sky-image pixels contributing to each observed longitude-sine(latitude) bin. |

2 Processing Stages and Code Layout

The following sub-sections provide a basic map of the various processing stages required to ingest HMI sky-image magnetograms and output SOLIS–spatial-variance–style synoptic maps. These
stages include:

1. Ingest and prep of HMI sky images (§2.1).
2. Remapping of sky images into Carrington-longitude–sine(latitude) heliographic maps (§2.2).
3. Combining heliographic remaps into synoptic maps (§2.3).

### 2.1 Ingest of Sky Images

In order to prepare the HMI magnetograms for heliographic and synoptic mapping, a few things need to happen, including: download the magnetograms from the Joint Science Operations Center (JSOC) site, update the image orientation and a few FITS-header keywords to comply with SOLIS-pipeline expectations, and — in the case of the vector magnetograms — calculate the heliographic magnetic-vector components from the HMI input frames. The layout of the code calls looks like this:

1. **Call** `backfillMagnetograms.sh N1 N2`:

   - For each day $N1$ to $N2$ days ago, requests a download of the UT 00:00 and UT 12:00 magnetograms from JSOC and places the results in an NSO-accessible data-keep directory.

2. **Call** `hmi_serrmaps_intake2fits_BatchRun.sh [-v] START STOP OUTDIR`:

   - For each day from $START$ to $STOP$:
     - Searches for available downloaded JSOC files, `INFILEs`.
     - Calls `hmi_serrmaps_intake2fits [-v] INFILE OUTDIR`
       
       → Opens the rice-compressed `INFILE` file.
       → Rotates the FITS image by $180^\circ$ to place Solar-north at the top.
       → Re-writes the FITS header using SOLIS-style sectioning.
       → Adds (primarily duplicate) keywords to the FITS header to account for the updated image geometry and allow for data read-in by SOLIS downstream processing.
       → Outputs the results to a gzipped file placed in a data keep within `OUTDIR` and using the NSO-style file-naming conventions.

3. **IF(vector):** Call `hmi_serrmaps_intakevbundle_BatchRun.sh START STOP`:

   - For each day from $START$ to $STOP$:
     - Searches for available ingested gzipped FITS files with flavor tag `type-b-720s-field`, `FIELDFILEs`.
     - In IDL, calls `hmi_serrmaps_intakevbundle`, `FIELDFILE`
       
       → Using input `FIELDFILE` filename to extrapolate, reads in the full file set necessary (`-field`, `-inclination`, `-azimuth`, `-disambig`) to compute magnetic-flux vector components.
       → Applies the disambiguation results (Radial-acute in the quiet sun) to the azimuth image by adding $180^\circ$ to all pixels where disambig is true.
       → Calls `chcoord3.pro` to define the heliographic coordinates of each image pixel.
→ Computes the line-of-LOS and transverse magnetic-vector components, then rot-
tates them into the local-surface heliographic plane(s).
→ Outputs the three frames of heliographic vector components into a FITS file
with the flavor tag ‘_type-b-720s-helio’.

**LOS magnetograms:** For the LOS magnetograms, an example output image (from step 2) is
shown in Figure 3. These FITS files have only a single image frame, containing the LOS magnetic
flux measured by HMI. They are given file names with the structure:

‘x4x72YYMMDDtHHMMSS_source-SDO-HMI_type-m-720s.fits.gz’

- ‘x4x72’: This is the product code that denotes HMI sky images of photospheric longitudinal
  magnetograms.
- ‘YYMMDDtHHMMSS’: This is the observation’s time-stamp.
- ‘_type-m-720s’: This indicates HMI–line-of-sight–magnetogram source data, regardless of im-
  age type.

**Vector magnetograms:** For the vector magnetograms, an example file set of ingested (output
from step 2) data are shown in Figure 4. In the ‘-azimuth’ file, angles are measured from the +y
image axis and increase counter-clockwise. In the ‘-disambig’ file, true values for the Radial-acute
disambiguation are indicated with integer values 4,5,6 and 7 (for Random disambiguation: 2,3,6,7;
for Potential-acute disambiguation: 1,3,5,7).

The frames for the corresponding heliocentric–magnetic-vector–components file (output from
step 3) are shown in Figure 5. These final-vector sky-image output FITS files have naming struc-
tures and frame contents as outlined below.

**Filename Structure:**
‘x4x92YYMMDDtHHMMSS_source-SDO-HMI_type-b-720s-helio.fits.gz’

- ‘x4x92’: This is the product code that denotes HMI sky images of photospheric vector mag-
  netograms.
- ‘YYMMDDtHHMMSS’: This is the observation’s time-stamp.
Figure 4: Set of example input image frames for an HMI-Vector magnetogram taken Oct. 18th, 2015 at 00:00 UT.

Figure 5: Set of example image frames for an HMI-Vector-derived Heliocentric-vector magnetogram observed Oct. 18th, 2015 at 00:00 UT.

- `type-b-720s-helio`: Regardless of image type, this indicates HMI-vector-magnetogram source data mapped into heliocentric vector components.

**FITS-frame Contents:**

| frame | units | title / description |
|-------|-------|--------------------|
| 1     | Gauss | Radial flux (outward):<br> HMI b_720s magnetogram radial-flux vector component. |
| 2     | Gauss | Poloidal flux (southward):<br> HMI b_720s magnetogram poloidal-flux vector component. |
| 3     | Gauss | Toroidal flux (+longitude-ward):<br> HMI b_720s magnetogram toroidal-flux vector component. |
2.2 Heliographic Remaps

Once the HMI sky images have been prepared for ingest into SOLIS synoptic-map processing (2.1), the next step is to map each image into a grid of longitude-sine(latitude) heliographic coordinates, as follows:

4. Call `hmi_serrmaps_remap_BatchRun.sh [-v] START STOP OUTDIR`:

   - For each day from `START` to `STOP`:
     - Searches for available prepped sky images, `SKYFILE`s.
     - In IDL, calls `hmi_serrmaps_remap`, `SKYFILE`, `OUTDIR`, `/tokeep`, `/sinlat`:
       → Reads in the `SKYFILE` image frame(s).
       → Calls `chcoord3.pro` to define the heliographic coordinates of each image pixel, and for all four corners of each pixel.
       → **IF (longitudinal)**: Projects the line-of-sight flux values into purely radial flux values (as per Equation 1).
       → Defines the Carrington-longitude bounds for the observation to set the bins for the heliographic output map.
       → Sorts all on-disk image pixels into weighted longitude-sine(latitude) bins. Pixels that cover multiple heliographic bins may be broken up into as many as 25 (5x5) sub-pixels for heliographic binning. (**Note:** This matches the spatial resolution of the SOLIS spatial-variance-map sub-pixel binning, where image pixels are broken up into 10x10 sub-pixels but derive from observations of half the spatial resolution as HMI.)
       → For each heliographic bin, computes:
         - the sum-of-weights (number of contributing pixels)
         - the mean magnetic flux
         - the RMS flux variance
         - the sum of squared weights
         - the mean of squared fluxes
       → **Note:** For vector magnetograms, the mean, RMS, and mean-squared fluxes are computed individually for all three vector components.
     → Outputs the resulting heliographic maps of computed quantities into a FITS file using the NSO-style file-naming convention and placed in a data keep in `OUTDIR`.

**Pseudo-radial Heliographic Maps:** An example of the frames output for a pseudo-radial heliographic map are shown in Figure 6. These FITS files have naming structures and frame contents as outlined below.

**Filename Structure:**

`x9x73YYMMDDtHHMMSS_map-err_dim-180_source-SDO-HMI_type-m-720s.fits.gz`

- `x9x73`: This is the product code that denotes HMI heliographic remaps of photospheric longitudinal data.
- `YYMMDDtHHMMSS`: This is the observation’s time-stamp.
Figure 6: Set of example image frames for an HMI-LOS-derived heliographic remap for an observation taken Dec. 1st, 2013 at 00:00 UT.

- *type-m-720s*: Regardless of image type, this indicates HMI–line-of-sight–magnetogram source data.

**FITS-frame Contents:**

| frame | units   | title / description                                      |
|-------|---------|----------------------------------------------------------|
| 1     | Gauss   | **Weighted-mean Radial Flux Density:**                    |
|       |         | Mean of radially-projected HMI-LOS magnetic flux at each heliographic bin. |
| 2     | Gauss   | **Spatial RMS Estimate:**                                 |
|       |         | Statistical variance of all radially-projected HMI-LOS-flux values at each heliographic bin. |
| 3     | Gauss²  | **Mean squared-Radial Flux:**                            |
|       |         | Mean of squared pseudo-radial flux values at each heliographic bin. |
| 4     | counts  | **Sum-of-Weights:**                                       |
|       |         | Sum of weights (image-pixel fractions) into each heliographic bin. |
| 5     | counts² | **Sum-of-squared-Weights:**                               |
|       |         | Sum of squared-weights into each heliographic bin.        |
Vector Heliographic Maps: An example of the frames output for a vector heliographic map are shown in Figure 7. These FITS files have naming structures and frame contents as outlined below.

Filename Structure:
'x9x93YYMMDDtHHMMSs_map-err_dim-180_source-SDO-HMI_type-b-720s-helio.fits.gz'

- ‘x9x93’: This is the product code that denotes HMI heliographic maps of photospheric vector magnetograms.
- ‘YYMMDDtHHMMSs’: This is the observation’s time-stamp.
- ‘_type-b-720s-helio’: Regardless of image type, this indicates HMI-vector-magnetogram source data mapped into heliocentric vector components.
### FITS-frame Contents:

| frame | units | title / description |
|-------|-------|---------------------|
| 1     | Gauss | **Mean Radial (outward) Flux Density:**  
|       |       | Mean of HMI-vector radial flux at each heliographic-coordinate bin. |
| 2     | Gauss | **Mean Poloidal (southward) Flux Density:**  
|       |       | Mean of HMI-vector poloidal flux at each heliographic-coordinate bin. |
| 3     | Gauss | **Mean Toroidal (+longitude-ward) Flux Density:**  
|       |       | Mean of HMI-vector toroidal flux at each heliographic-coordinate bin. |
| 4     | Gauss | **Radial-flux Spatial RMS Estimate:**  
|       |       | Statistical variance of all HMI-vector radial-flux values into each heliographic-coordinate bin. |
| 5     | Gauss | **Poloidal-flux Spatial RMS Estimate:**  
|       |       | Statistical variance of all HMI-vector poloidal-flux values into each heliographic-coordinate bin. |
| 6     | Gauss | **Toroidal-flux Spatial RMS Estimate:**  
|       |       | Statistical variance of all HMI-vector toroidal-flux values into each heliographic-coordinate bin. |
| 7     | Gauss² | **Mean squared-Radial Flux:**  
|       |       | Mean of squared radial-flux values at each heliographic-coordinate bin. |
| 8     | Gauss² | **Mean squared-Poloidal Flux:**  
|       |       | Mean of squared poloidal-flux values at each heliographic-coordinate bin. |
| 9     | Gauss² | **Mean squared-Toroidal Flux:**  
|       |       | Mean of squared toroidal-flux values at each heliographic-coordinate bin. |
| 10    | counts | **Sum-of-Weights:**  
|       |       | Sum of weights (image-pixel fractions) into each heliographic-coordinate bin. |
| 11    | counts² | **Sum-of-squared-Weights:**  
|       |       | Sum of squared-weights into each heliographic-coordinate bin. |
2.3 Compiling Synoptic Maps

Once all of the heliographic remaps have been processed (§2.2), they can be assembled into Integral synoptic maps covering the full 360° of Carrington longitude, as follows:

5. Call `hmi_serrmaps_synoptic_BatchRun.sh [-v] START STOP CARRFILE`:

- Uses `CARRFILE` to look up the date ranges of the Carrington rotations, `CARRNUMs`.
- For each `CARRNUM` occurring between `START` and `STOP`:
  - Calls the IDL routine `hmi_serrmaps_synoptic.pro` for the specified `CARRNUM` and data type (HMI-LOS or HMI-Vector):
    - Looks up the date range covered by `CARRNUM` and searches the data keep for a list of all available heliographic remaps falling within that date range +/- an additional 8 days.
    - Reads in the headers of the listed heliographic files in order to:
      * Define the range of longitude bins covered by each heliographic map.
      * Discard from the list any heliographic maps that fall entirely outside the 0-360° longitude of `CARRNUM` (e.g., usually discards the maps from observations taken 8 days before and after the Carrington-rotation date bounds).
      * Double-check various observation-quality keywords and discard any heliographic maps that fail.
    - For each heliographic-map file, `HRFILE`, retained from the file list:
      * Reads in the `HRFILE` image frames.
      * Rescales the values in the Weights frame by $\cos^4(\Delta \text{longitude})$ with respect to the central meridian.
      * Places all in-bounds heliographic-map data into the synoptic-map image space. In this step, each heliographically mapped quantity for this observation (weights, fluxes, etc.) is saved into its own synoptic-map of an $nfiles$ stacked set.
    - Once all of the heliographic maps have been loaded into the synoptic-map space, computes:
      - the sum of weights in each synoptic-map bin
      - the mean weighted-flux values in each synoptic-map bin
      - the spatial variance of the flux values in each synoptic-map bin
    - **Note a:** For vector maps, the mean-flux and spatial-variance values are computed individually for all three vector components.
    - **Note b:** For any synoptic-map bin where the sum-of-weights equals 0, the mean-flux value(s) is set to 0, and the spatial-variance(s) is flagged with the nonsense value -1000.
    - **IF(HMI-longitudinal):** Calls `hmi_serrmaps_polefiller_sfit.pro` to return a pole-filled version of the radial-flux map.
    - Outputs the final synoptic maps of computed quantities into a FITS file using the NSO-style file-naming convention outlined in §1.

This is the final stage of processing, which produces the data-product files described in §1.
3 Notes on HMI Disambiguation

Creation of synoptic maps from HMI magnetograms required a few choices as to the handling of the HMI data, and primary among them was which quiet-sun disambiguation results should be employed to project the observed vector fields into heliographic coordinates.

The -disambig file included with all HMI-vector magnetograms in the b_720s series provides the HMI-disambiguation results as an image of true/false values answering whether the azimuth angle at a given pixel should be rotated by 180° relative to the value provided in the -azimuth file (Hoeksema, et al., 2014). For strong-field and near-strong-field pixels, the disambiguation is the result of “annealing” using a minimum-energy algorithm. For weak-field pixels, the -disambig file provides results from three different disambiguation algorithms:

1. A Potential-acute algorithm that works to align the field with a potential field extrapolated from the vertical field component.

2. A Random disambiguation assignation.

3. A Radial-acute algorithm that selects the disambiguation that most closely aligns the field in the purely radial direction.

The HMI documentation (JSOC Wiki - Disambiguation, 2014) recommends using #2, where the weak-field disambiguation is randomly assigned. However, for these synoptic maps, we have chosen to employ the radial-acute disambiguation results, which produce clearer signatures of the synoptic magnetic field in the quiet sun, as can be seen in Figure 8.

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Figure 8: For Carrington rotation 2161 centered around March 14th 2015, a comparison of HMI-vector synoptic maps produced using the **Radial-acute** (left column) versus **Random** (right column) weak-field disambiguation results. From top to bottom, the rows plot the mean-radial, -poloidal, and -toroidal flux, with a greyscale stretching from -20 to +20 Gauss.

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