Discussion of likely bug in the HMI production code for LOS lookup tables and LOS Dopplergram code. 11 Jan 2022

Background

The HMI onboard tuning is set to 72 degrees of phase between steps of the WB Michelson. With 6 sampling points with 5 steps of 72 degrees, this covers 360 degrees, or 1 WB FSR. See e.g. proj/lev1.5_hmi/apps/HMI_lookup.c lines 742:764:

```
if(N == 6)
 {
  HCME1phase[0]= (double) ((HCME1+15)*6 % 360)*M_PI/180.0; //I0 = 90 degrees
  HCME1phase[1]= (double) ((HCME1+9 )*6 % 360)*M_PI/180.0; //I1  = 54
  HCME1phase[2]= (double) ((HCME1+3 )*6 % 360)*M_PI/180.0; //I2  =  18
  HCME1phase[3]= (double) ((HCME1-3 )*6 % 360)*M_PI/180.0; //I3  = -18
  HCME1phase[4]= (double) ((HCME1-9 )*6 % 360)*M_PI/180.0; //I4  = -54
  HCME1phase[5]= (double) ((HCME1-15)*6 % 360)*M_PI/180.0; //I5  = -90

  HCMWBphase[0]= (double) ((HCMWB-30)*6 % 360)*M_PI/180.0; // = -180 degrees
  HCMWBphase[1]= (double) ((HCMWB-18)*6 % 360)*M_PI/180.0; // = -108
  HCMWBphase[2]= (double) ((HCMWB-6 )*6 % 360)*M_PI/180.0 ; //  =  -36
  HCMWBphase[3]= (double) ((HCMWB+6 )*6 % 360)*M_PI/180.0; //  =   36
  HCMWBphase[4]= (double) ((HCMWB+18)*6 % 360)*M_PI/180.0; //  = 108
  HCMWBphase[5]= (double) ((HCMWB-30)*6 % 360)*M_PI/180.0; //  = 180

  HCMNBphase[0]= (double) ((HCMNB-0 )*6 % 360)*M_PI/180.0;    //  = 0 degrees
  HCMNBphase[1]= (double) ((HCMNB+24)*6 % 360)*M_PI/180.0;  //  = 144 == -216
  HCMNBphase[2]= (double) ((HCMNB-12)*6 % 360)*M_PI/180.0;  //  = - 72
  HCMNBphase[3]= (double) ((HCMNB+12)*6 % 360)*M_PI/180.0; //  =  72
  HCMNBphase[4]= (double) ((HCMNB-24)*6 % 360)*M_PI/180.0;  // = -144 == 216
  HCMNBphase[5]= (double) ((HCMNB+0 )*6 % 360)*M_PI/180.0;  // =  0
```

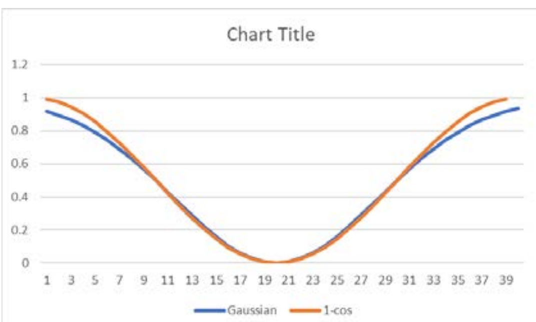
There are 240 motor steps per rotation so each step is 1.5 degrees of rotation of the half-wave plates. One degree of rotation is 4 degrees of phase so the steps are 6 degrees. The full tuning range is 2 NB FSR, 1 WB FSR, and 0.5 E1 FSR. The steps are for NB 144 degrees, WB 72 degrees, and E1 36 degrees between tuning angles.

This code is present in various forms in the Phasemap making code, the lookup code, and vfisv code.

For the Fe line at 6173.3433 Angstroms the conversion of angstroms of shift to velocity is dlamdv in some codes, = 2.0592E-5 angstroms per m/s or dVdLam = 48,562 m/s per Angstrom. The values for FSR used in the code since just after launch are in NB, WB, E1 order

'NB':0.168900, 'WB':0.336850, 'E1':0.695000

In Angstroms, so the full tuning range is 16,404 m/s or +- 8,202 m/s. The spacing between tuning positions is 3,281 m/s as set by 2 * NBFSR or about 1 * WBFSR.
The NB FSR is about half the WB FSR, such that 2*NBFSR / WBFSR is 1.00282. If measured in 1/5 of WBFSR then the velocity per tuning step is 3272 m/s. The difference between using WBFSR and NBFSR at the limb at orbit of 3000 m/s is then 15 m/s. Since that is much smaller than the amplitude of the 24-hour orbit leakage the discussion of which to use can be set aside for the moment. All of the production code uses 2 * NBFSR for the tuning range since the NB filter has more resolution. The combined effect on the centroid of the final instrument profile Is much smaller than the 0.2% difference. So not an issue at the moment.



The MDI-like method of finding the wavelength of the line position comes from the idea that the line is nearly a gaussian shape, or rather 1 – a gaussian of peak of line-depth, shown in a plot of 2 * FWHM looks like 1-cosine, and since the location of the peak in that width of plot is just the phase of the first Fourier component of a fit to the gaussian. For MDI the FSR of the combined Michelsons was selected to be about twice the FWHM of the Ni 6768 line. With 4 tuning positions positioned equally spaced over this width, i.e. 90 degrees apart, at -135, -45, 45, 135 degrees then the cos and sin of these is -.707, +.707, +.707, -.707 and -.707, -0.707, +.707, +.707.
Or dividing each by 0.707, one gets cos = -1, 1, 1, -1 and sin = -1, -1, 1, 1 then combining these in the sums one gets a ratio of differences which means that the MDI velocity does not depend on a correct flat field or intensity scale. But the range is limited to a small part of the FSR since the line outside the 2*FWHM is not sinusoidal.

HMI needs a larger tuning range since it has the orbit velocity and splitting from Zeeman splitting of the line. It needs a range of +- 3000 (orbit), 2000 (rotation), 500 (p-modes), 300 (supergranules), 1500 (granules), 4000 (2000 G field). Fortunately, these do not all add since most depend on view angle so a goal of +- 5000 for velocity and an additional 2000 for LOS fields (4000 disk center, 0 at limb.) So, the minimum range needs to be c. +-7000 m/s.
The Fe 6173 line has FWHM of about 76mA, the MDI like FSR would be 152mA, and it corresponds to about 3700 m/s so we need a range about 4 * the line width, about twice the MDI design. The WBFSR is a bit larger than this goal.

Now finally the problem. Note that to find the phase using the FSR as a wavelength scale, we make steps equal to, in HMI case, 1/6 of the WBFSR – but instead of placing the 6 tuning positions as if we were going to fit the Fourier components over the span of 1 WBFSR i.e, with separations of FRS/6, or 60-degree steps, we use steps of FSR/5 so have samples at + and – the WBFSR with 72 degree steps between for the 4 equally spaced samples.

However the code used to fit the line phase within the tuning range, 2*NBFSR, is to fit sine and cosine components to the 6 intensity points assuming steps of 2*NBFSR/6, or 60-degree steps with 5 steps of 60 and 30 degrees at each end of the span. The formula implemented in the code is to sum the product of cosine and sine values at each tuning angle multiplied by the intensity observed at each of the six tune positions used onboard HMI. The cosine fit for the first Fourier component is thus:

$$a_1 \approx \frac{2}{6}\sum_{j=0}^{5} I_j \cos\left(2\pi\frac{2.5-j}{6}\right)$$

With a span of 5/6 of 2 pi, but without any wavelength scale. But in 60 degree steps assuming that the span is for equally spaced samples. The phase within this wavelength span is defined by the scale applied to the total span, originally in the code intended to be for one WBFSR. By the 6 actual tunings also equally spaced over a range of one fifth of a WBFSR larger than the intended scale. Once the phase is determined by the arc tangent of the sum of sines divided by the sum of cosines then the scale can be applied to convert phase into velocity.

The lookup table code, HMI_lookup.c and the Doppler calibration in the Dopplergram.c code and its successors for other changes both assumed that the scale should be 2 NBFSR over 2 pi of phase. But for the onboard sampling with 5 spaces of 72 degrees can be used with these equally spaced samples but with a phase to wavelength scale expanded by 72/60, or 1.2 larger than 2 NB FSRs. If the plan had been To make 6 samples equally spaced over a span of an FSR that was 1.2 * WBFSR the samples would take accidental advantage of a portion of the range of the E1 element. So by using 1.2 times the NBFSR one has again 6 samples equally spaced over the a span of wavelength, just not the planned span.

So basically the same algorithm can be used with a correction to the intended span of wavelength. This has been tested by increasing the, lets call if the reference span, or refFSR which is now in the range of 1.2 * WBFSR or 2.4 * NBFSR. So now the total span is about 0.40422 to 0.40536 Angstroms. And the range of velocities expands to 19630 to 19,685 m/s with a step between samples of 3926 to 3937 m/s between tuning steps. These would have been the ranges if we had intended to make more use of the tunable narrowest Lyot element, E1.

Since we use the actual filter profiles to compute the instrument transmission profiles for each of the 6 samples and use those 6 profiles each constrained by the non-tunable part of the filter sections and convolved with the line profile as a measure of the expected signal for each of the 6 samples then we can continue to use these for the Line-of-Sight calibrations.

For the use of the Stokes samples since we use these same 6 transmission profiles in the more complex fitting of vector field components as well as other features of the Sun at the pixel locations the vector field analyses will not be impacted by this refFSR issue so long as what is used is the 6 filter profiles with enough range in wavelength to sample the leaks and detailed shapes of the transmission profiles.

I believe that the present code was originally designed for the option of making two configurations of 5 samples, one more toward the red and one to the blue to be used in different parts of the day as a 5-sample measurement. In that case the phase scale would have used the 2 * NBFSR as the code is now written but taking into account the change in the zero point of the profile ensemble.

For a test of this issue using 3 days in the early mission, February 18, 19, and 20 in 2011. A test of old code for that time shows a variation of peak-to-peak 1200 m/s of the Dopplergram mean value, out of phase with OBS_VR by 180 degrees. When the factor of 1.2 was applied to both the lookup table code and the Doppler calibration code this was reduced to a span of 100 m/s still with phase opposite to OBS_VR. When the refFSR was further changed to the slightly larger NBFSR of 0.1725 as indicated in an early pre-launch description the range was reduced to 40 m/s with the same phase as OBS_VR suggesting that this was too large. Assuming a linear relation, a revised value of 0.1715 was used with the peak to peak of both the 24 hour and 12 hour peaks to be 20 m/s peak to peak.

In the pre-launch and first several months values of 0.1689, 0.1690 0.1709, and 0.1723 were tested with each of these being in the range allowed by the ground calibrations of the filter elements. The statement at the time and in the published on-orbit calibration plans the intent to use the well known orbit velocity to trim these values.

At present the production code has the lines:

```
double dtune   = FSR[0]/2.5;    //nominal wavelength separation between each tuning position:
                //we use 2.5 so that the spacing is the same for 5 or 6 positions
double dvtune  = dtune/dlamdv;
pv1 = dvtune*(double)(N-1); //WARNING THIS IS WRONG, SHOULD BE dvtune*(double)N
vRCP    = atan2(-f1RCPs,-f1RCPc)*pv1/2.0/M_PI;
```

The fact that the use of the incorrect value was known suggests that the current version of the code was intended as some test, and not the final code. Sebastien Couvidat did not use any code version control so this can not be verified. There were some changes in the strength of the 24-hour leak into the Doppler and LOS field during the early years, perhaps this was from a change that was not meant to be Left in the production code.

All of the LOS products, V, M, Ic, Lw, Ld are affected by the wrong wavelength scale in the present code.