Calibration Plan:
Filter Transmission

Wavelength Dependence and Spatial Dependence

Purpose

In order to accurately measure the Doppler velocity we need to know the calibration data of the front window, blocker, Lyot, and Michelson filters.

Requirements

The IPD specifies the noise on the Doppler velocity determination: 25 m/s in quiet Sun, for a dynamic range of ±6.5 km/s.
The CPS specifies a baseline filter design with a 76 mA FWHM, a central wavelength of 6173 A (Fe I line) and a filter range of 680 mA.
The IPD specifies that the ripples of the front window and blocker filter should be less than 1% of the maximum transmittance.

Test configuration

All configurations can be used.

Needed measurements and test plans

Measurements are made on the complete instrument ---only one CCD is required---, preferably in vacuum, otherwise in air. An air-to-vacuum corrector could be applied at the entrance of the telescope to make it in focus, but this is not necessary since we will spatially average the output maps.

Measurements are to be done in Obsmode and Calmode. Both are

needed because the cones ---over which the light rays reaching a specific CCD pixel are integrated--- are not the same in these 2 modes, and because we need to separate the impact on the transmission profile of the front window ---that is in focus in Calmode but not in Obsmode--- from the impact of the blocker filter.

In Calmode:

Measurements might be made with a laser illuminating a circular target whose size is the angular diameter of the Sun. A dye laser is needed. The stimulus telescope will be placed in between the laser and the front window of the instrument. The circular target should be placed in the focal plane of the stimulus telescope.

The test sequence includes: changing the laser central wavelength and running a detune sequence at each wavelength. From the output intensities measured on the CCD a computer code will characterize the filter system.

By characterization we mean: either determining the relative phases and contrasts of the 5 Lyot elements and of the 2 Michelsons, or determining the phases and contrasts of the tunable elements and reconstructing the profile of the non-tunable part of the filter by interpolation. We need to record the laser intensity during the test, through a fiber optic cable lighting a small area of the CCD, or with an external device. The filtergrams will be corrected for any variation in the laser intensity. The wavelength of the laser should also be accurately measured with a wavemeter.

We will pick a single detune sequence for the entire test: this detune sequence will have 27 positions at the most. It should be carefully chosen to avoid possible degeneracies between some filter parameters and to make the least-squares algorithm converge rapidly. The number of laser wavelengths also needs to be determined. The number used for MDI, 10, was too low. Simulations of the test sequence show that 32 wavelengths more or less equally spaced between -3.5 and +3.5 Angstroms should allow for an accurate reconstruction of the non-tunable part of the filter profile.

Additionally, the use of a lamp (plus a detune sequence) replacing the dye laser should allow for a partial reconstruction of the front

window+blocker filter transmission profile. A possible way of determining this profile from the measured intensities is to use the spatially averaged blocker filter profile as an input of a computer code and to expand the fringes profile in a Fourier series: we then fit for the amplitudes of the cosines and sines of the series.
The output intensities are a linear combination of some Fourier coefficients of the blocker+window+non-tunable Lyot transmission profile. Therefore, we can derive the spatial frequencies that the lamp test will give us access to. For this analysis to work we must know the FSRs, phases, and contrasts of all the Lyot and Michelson elements (or the transmission profile of the non-tunable Lyot filter). Therefore this lamp test must be run after these parameters have been determined. A specific detune sequence may be chosen for this test, or we may use the same one as the laser test.

In Obsmode:

The same measurements are to be done.

Measurements could also be done in sunlight using an heliostat, if there is enough time, to account for the impact of the solar line broadening near the limb (and intensity reduction) on the Doppler velocity error. The solar p-angle must be determined and recorded for the time and date of the test.

Data analysis and needed software

The data returned by the detune sequence are filtergrams, which will probably be stored as *.fits* files. Two programs that convert these filtergrams into the filter parameters are needed. One program will be based on the laser test data, and the other one will be based on the lamp test data.

Ideally the first program will perform a least-squares algorithm to fit for the contrasts and phases of each Lyot and Michelson element, or at least for the tunable elements. It will use the spatially-averaged transmission profile for the blocker filter already obtained at Lockheed Martin, and the FSRs already measured on the individual elements. If not

fitted for, the non-tunable part of the HMI filter can be retrieved by interpolating the measured intensities. A spline interpolation is likely to be used, providing fast and reliable results. A sine transform interpolation could also be performed, but the non-uniform wavelength sampling rate of the dye laser complicates the procedure.
The 4096x4096 output intensities, measured on the CCD, will probably be averaged by 32x32 blocks, to improve the poor signal-to-noise ratio due to a high dark current level. Moreover, the least-squares fit will probably be regularized because of this poor S/N ratio, especially if the test is done in air (making it difficult to cool down the CCDs).
We can reasonably assume that the input transmission profile from the laser is a simple delta function. If it turns out that the width of the laser line (expected to be less than 1 mA) is not negligible, this width ---like the wavelength--- must also be taken into account in the code as a known parameter. The Jacobian matrix of the least-squares fit is used to determine which detune sequence allows for a precise determination of the parameters we are interested in.

The second program will use the spatially-averaged blocker filter transmission profile, the tunable Lyot+Michelson parameters, and the data related to the non-tunable part, as returned by the first program, and will fit for the amplitudes of 7 cosines and sines.

This wavelength and spatial dependence calibration test may be combined with the angular dependence test. The codes need to return the filter calibration parameters for each CCD pixel in Obsmode and Calmode (i.e. the output data are maps), and also the spatial averages.

Angular Dependence

Purpose

In order to accurately measure the Doppler velocity we need to know how the calibration data of the front window, blocker, Lyot, and Michelson filters vary as a function of the angle of incidence of the light rays.

Requirements

The IPD specifies the noise on the Doppler velocity determination: 25 m/s in quiet Sun, for a dynamic range of ±6.5 km/s.
The CPS specifies a field of view of 2000'' for HMI.

Test configuration

All configurations can be used.

Needed measurements and test plans

Measurements are made on the complete instrument (only one CCD is required), preferably in vacuum, otherwise in air (an air-to-vacuum corrector could be applied at the entrance of the telescope to make it in focus). Measurements are to be done in Obsmode and Calmode. Both are needed because the cones ---over which the light rays reaching a specific CCD pixel are integrated--- are not the same in these 2 modes, and because we need to separate the impact on the transmission profile of the front window ---that is in focus in Calmode but not in Obsmode--- from the impact of the blocker filter.

<u>In Calmode:</u>

Measurements might be made with a laser lighting the stimulus telescope placed in front of the HMI instrument, to feed the instrument with a perfectly collimated bunch of rays. A dye laser is needed. The angular dependence test should be performed immediately after the

wavelength and spatial dependence test, or combined with this test.
In a first approximation, a non-zero incidence angle ø adds to the normal retardance of a Lyot or Michelson element a term proportional to $ø^2$ (for small ø). The corresponding change in FSR for the element is negligible and the main effect is a wavelength drift amounting to a phase shift and expected to be proportional to $ø^2$.
For a given laser wavelength, we should run one detune sequence per incidence angle. When analyzing the test data (output intensities measured on the CCD) we will use the FSRs and contrasts of the filter elements already derived from the wavelength and spatial dependence test, and we will fit for the angle-dependent phases of the Lyot and Michelson elements. Alternatively, if the non-tunable Lyot transmission profile has been interpolated with the wavelength and spatial dependence test data instead of being parameterized, then we will just measure the shift in wavelength of this non-tunable part transmission profile. The laser intensity and wavelength should both be recorded during the test.
One laser wavelength and detune sequence is enough to fit for the tunable part parameters. Several wavelengths are needed for the non-tunable part: the exact number needs to be determined from a numerical simulation. The detune sequence should be the same as the one used in the wavelength and spatial dependence test.
We should measure output intensities for 6 different incidence angles ranging from -0.28° to +0.28° (to cover the field of view of HMI). No azimuthal dependence is expected but two series of measurements should nonetheless be performed to check the accuracy of this assumption: one series with angles varying vertically and one with angles varying horizontally. The specific angles can be selected either by moving the legs of the HMI instrument ---to change the instrument orientation related to the collimated rays--- or by moving the optical fiber cable that guides the laser beam. The exact value of the selected angle can be retrieved by taking an image of the laser dot in Obsmode: the radial distance of the CCD pixel that receives the laser light to the CCD center is related to this incidence angle.

<u>In Obsmode:</u>

Measurements might be made with a laser illuminating a circular

target whose size is the angular diameter of the Sun. A dye laser is needed. The stimulus telescope will be placed in front of the instrument. To select the incidence angles, an opaque mask will be punctured and placed in between the stimulus telescope and the HMI front window. Depending on the location of the pinhole (its radial distance from the center of the HMI aperture), a specific incidence angle is selected. By rotating the mask about the optical axis of the HMI instrument and stimulus telescope, we can derive the spatial variation of the instrument response to this specific incidence angle. A detune sequence will be run for each angle.

Measurements should also be done in sunlight using an heliostat, if there is enough time, to account for the impact of the solar line broadening near the limb (and intensity reduction) on the Doppler velocity error. The solar p-angle needs to be determined and recorded for the time and date of the test.

Data analysis and needed software

The data returned by the detune sequence are filtergrams, which will probably be stored as *.fits* files. A program that converts these filtergrams into the filter parameters are needed. Ideally this program will perform a regularized least-squares algorithm to fit for the phases of each Lyot and Michelson element (or at least for the tunable elements), using the contrasts and the transmittance profile of the blocker and front window that have been returned by the wavelength and spatial dependence test.

We can reasonably assume that the input transmission profile from the laser is a simple delta function. If it turns out that the width of the laser line (expected to be less than 1 mA) is not negligible, this width must be taken into account in the code as a known parameter. The Jacobian matrix of the least-squares fit is used to determine which detune sequence allows for a precise determination of the parameters we are interested in.

Stability

Purpose

In order to accurately measure the Doppler velocity we need to know how the calibration data of the front window, blocker, Lyot, and Michelson filters vary with temperature.

Requirements

The IPD specifies the noise on the Doppler velocity determination: 25 m/s in quiet Sun, for a dynamic range of ±6.5 km/s.

Test configuration

All configurations can be used.

Needed measurements and test plans

Measurements are made on the complete instrument in vacuum (only one CCD is needed). In a first approximation, a temperature change produces a wavelength drift on the transmission profiles (estimated, e.g., to 1 mA/°C for the transmission profile of the non-tunable Lyot). The other effects ---especially a change in the FSRs--- are negligible. Since the drift is expected to be very small for perfectly compensated Lyot and Michelsons, we should span a large range of temperature during the test. For instance we could select 3 temperatures: 25, 30, and 35 °C (range of the oven ?). Moreover, measurements will probably be made only with sunlight through an heliostat: we need a light source whose central wavelength is expected to drift by a much smaller amount than the wavelength drift due to the temperature change. Therefore, the stability of the light source should be better than 1 mA: on average the change in the earth orbital velocity is about 5.5 m/s a day, roughly meaning a maximum shift of 0.11 mA a day of the observed solar iron line. The stimulus telescope will be placed in front of the instrument, outside of the vacuum tank. The measurements will be made in Calmode only: in Obsmode, the

solar Fe line is not stable enough (due to acoustic oscillations !). Only marginal differences are expected in term of thermal stability between these two modes.

We will perform a detune sequence that will only give us access to the tunable part of the HMI filter. The output intensities, measured on the CCD, will be used as input parameters in a computer code. This code will fit for the phases of E1 and the 2 Michelsons (meaning 3 parameters to retrieve). The FSRs and contrasts of the tunable elements will be input parameters whose values are the ones returned by the wavelength and spatial dependence test. Either the transmission profile or the parameters of the non-tunable Lyot will be used as known input parameters. Therefore the stability test should be performed after the wavelength and spatial dependence test.

The detune sequence could be the same as the one used in the wavelength and spatial dependence test (with 27 positions at the most), plus an extra position to measure the intensity in the solar continuum. The width and depth of the solar line will be fitted for, using a simple Gaussian line model. The solar p-angle needs to be determined and recorded for the date and time of the test.

Data analysis and needed software

The data returned by the detune sequence are filtergrams, which will probably be stored as *.fits* files. A program that converts these filtergrams into the filter parameters are needed. Ideally this program will perform a regularized least-squares algorithm to fit for the phases of each tunable Lyot and Michelson element. It will use the other parameters of the Lyot and Michelson elements, and the transmittance profile of the blocker and front window that have been returned by the wavelength and spatial dependence test. The solar line central wavelength and depth will be fitted for.

The Jacobian matrix of the least-squares fit is used to determine which detune sequence allows for a precise determination of the parameters we are interested in.