Description of the Sensor Correction
FIR & IIR Filter Components

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1   Summary

We describe the components used to implement the FIR filter for the sensor correction used by HEPI to isolate the stage 0 platform from microseismic motion. The design of the basic FIR filter was done by Wensheng Hua, and described in his thesis. This document merely describes the necessary companion IIR filters used to complete the sensor correction path.
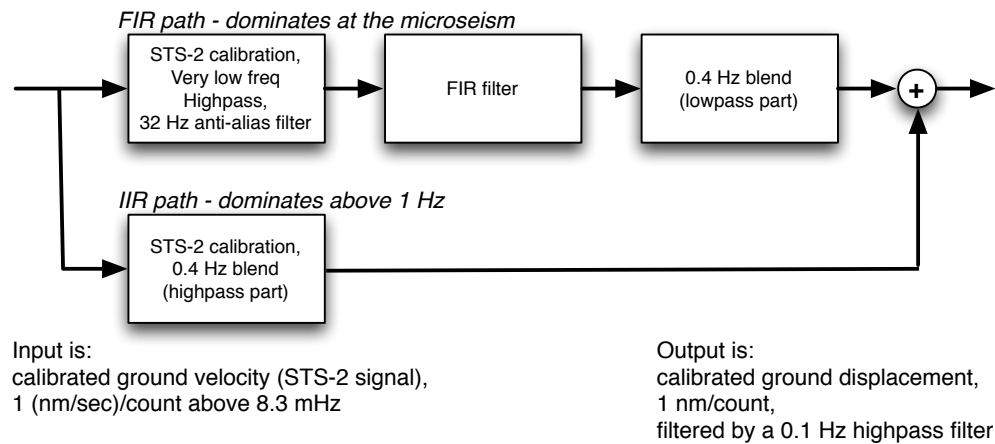
Figure 1: Components and flow for the sensor correction path. The parallel paths are mimic the CDS filter blocks which we use to implement various tricks described below. The STS-2 calibration is done on both paths for convenience of implementation.

The sensor correction block calculates the signal to be added to the in-loop displacement sensor. The goal is to calculate the ground displacement and highpass filter it so we accurately pass the ground displacement at the microseismic peak and higher frequencies, but we do not pass the ground tilt, which dominates the horizontal signals at lower frequencies.

The design of the 'optimal' filter for this is described in Wensheng Hua's thesis *Low Frequency Vibration Isolation and Alignment System for Advanced LIGO*, which is available at LIGO-P050030. A convex optimization technique was used to calculate the 'optimal' FIR filter, but the resulting filter is very computationally intensive, so a set of tricks are used to make the system realizable. Those tricks include the use of IIR filters to accompany the basic FIR filter. Figure 2 compares the basic FIR response to the final highpass consisting of the FIR and the IIR companion filters. The response near the microseism is the same, but the companion filters clean up the response below 10 mHz and above 1 Hz.
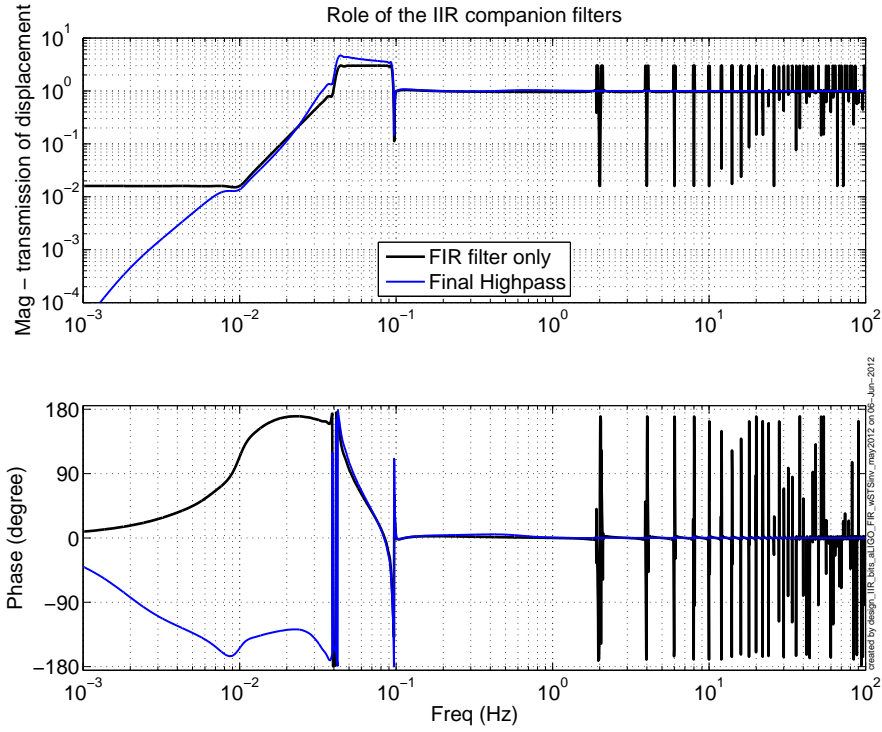

Figure 2: Comparison of the raw FIR filter and the Final Highpass. The Final Highpass uses both the FIR and several IIR companions filters.

2 The Parts

2.1 The parallel FIR and IIR paths

Conceptually, the sensor correction path first converts the calibrated STS-2 velocity signal into displacement, and then it highpass filters the displacement signal. [1] In reality, the calibrated STS-2 velocity signal is sent to two parallel paths, an FIR path and an IIR path. Each path inverts the STS-2 signal into displacement, and then the FIR path computes the low frequency part of the final highpass filter, and the IIR path computes the high frequency part of the final highpass filter. The 0.4 Hz blend filter used to combine the low frequency signals from the FIR path with the high frequency path is shown in figure 3.
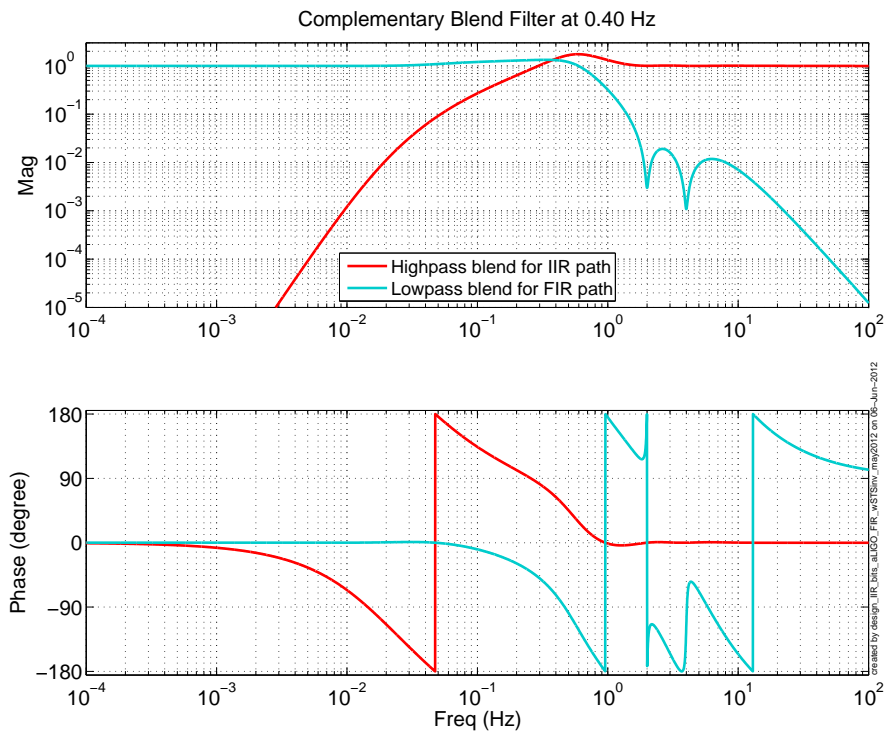

Figure 3: Complementary blend filters used to combine the low frequency signals from the FIR path with the high frequency signals in the IIR path.

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[1] The calibrated STS-2 signal is 1 count/(nm/sec) above 8.33 mHz, with two zeros at DC and two poles at 8.33 mHz. This is just a gain scaling of the original STS-2 response.

2.2 The FIR path

The FIR path computes the sensor correction signal below about 0.4 Hz. The first block of the FIR path (module 0 in the MEDM screen) is shown in figure 4. This block has 3 jobs. First, it inverts the STS-2 response, so we have a displacement signal. Second, it applies a very low frequency highpass filter. This highpass filter must have at least 4 DC zeros, so that we have an AC coupled system (the STS-2 inversion has 3 DC poles). The very low frequency highpass also assists the FIR filter by rolling off the very low frequency signals. The frequency response of FIR filters for periods longer than the filter history is fixed at some DC value, so IIR filters are better suited for very low frequency roll off. Finally, module zero has an anti-alias filter at 32 Hz. The FIR filter samples at 64 samples/ sec. The anti-alias filter is a 4th order elliptic with zeros at 64 and 128 Hz, and should be very good at keeping aliased noise out of the few Hz around DC. The anti-alias filter is unusual, because it allows aliasing of signals from 32 Hz and above almost, but not quite back down to DC. We really only care right around DC (64 Hz alias) because the IIR path will control the signals above 1 Hz, so we choose an anti-alias filter with very good phase performance at 1 Hz, but poor aliasing above a few Hz.
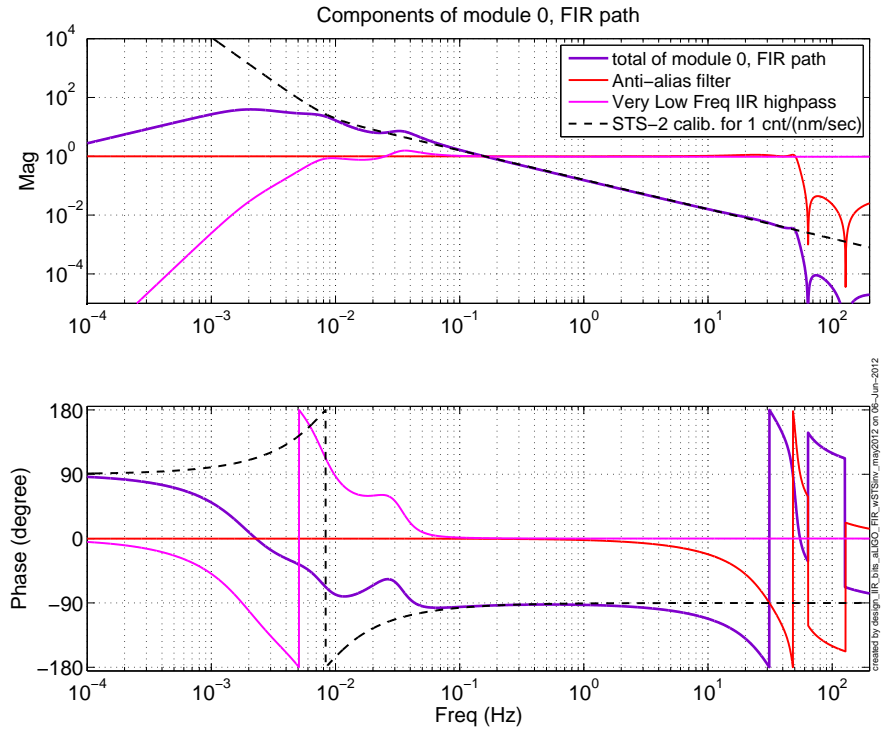
Figure 4: Module 0 of the FIR path. This filter set converts the STS-2 into displacement, rolls off the very low frequency signals, and has an anti-alias filter for the FIR. Note that the anti-alias filter has very little phase distortion below 1 Hz, which is achieved by only cutting off signals at about 64 Hz and above.

The second module is the polyphase FIR filter. This is a filter with very good gain and phase matching (i.e. very close to 1) above 0.1 Hz, and fast roll-off below 40 mHz. Further discussion can be found in Hua's thesis, LIGO-P050030.

The third module in the FIR path is the lowpass half of a complementary filter (see figure 3 with a blend frequency of 0.4 Hz, and notches at 2 Hz and 4 Hz to help suppress the bumps in the FIR response. Figure 5 shows the filters in each of the 3 modules and their product.
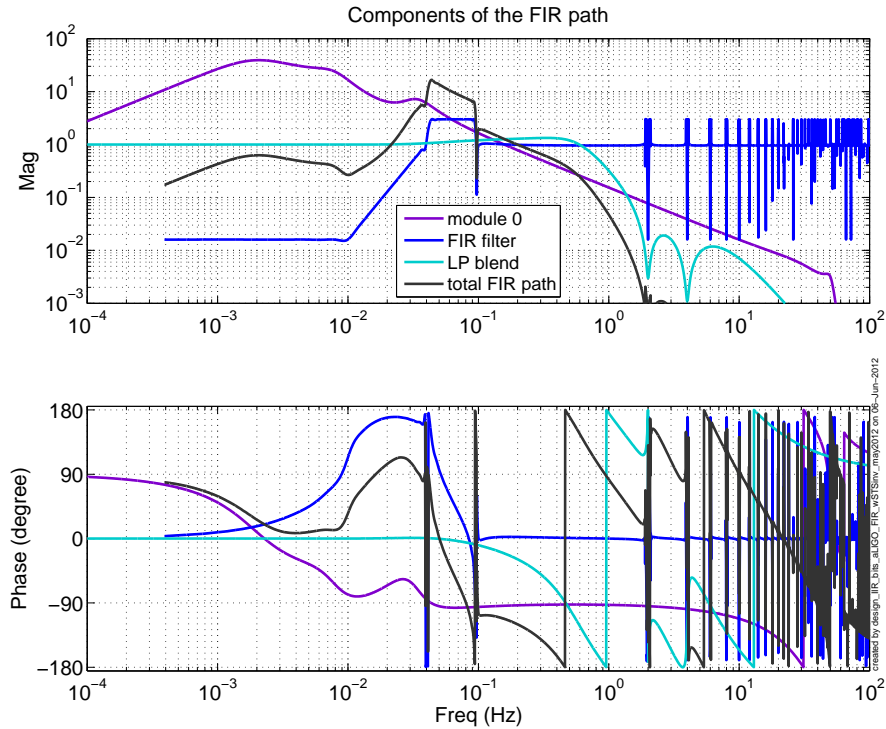
Figure 5: Components of the FIR path. There are 3 modules in the FIR path: *module 0*, (which converts the STS-2 signal into displacement, has a very low frequency lowpass, and an anti-alias filter, see figure 4), the *FIR filter*, and the lowpass part of a *blend filter* to combine the signal with the IIR path. The blend frequency is at 0.4 Hz (see figure 3), so this path controls the signal at the microseism and below.

2.3 The IIR path

The IIR path is very simple. It inverts the STS-2 response, so we have a displacement signal, and multiplies that by the highpass part of the 0.4 Hz blend filter. The components are shown in figure 6.
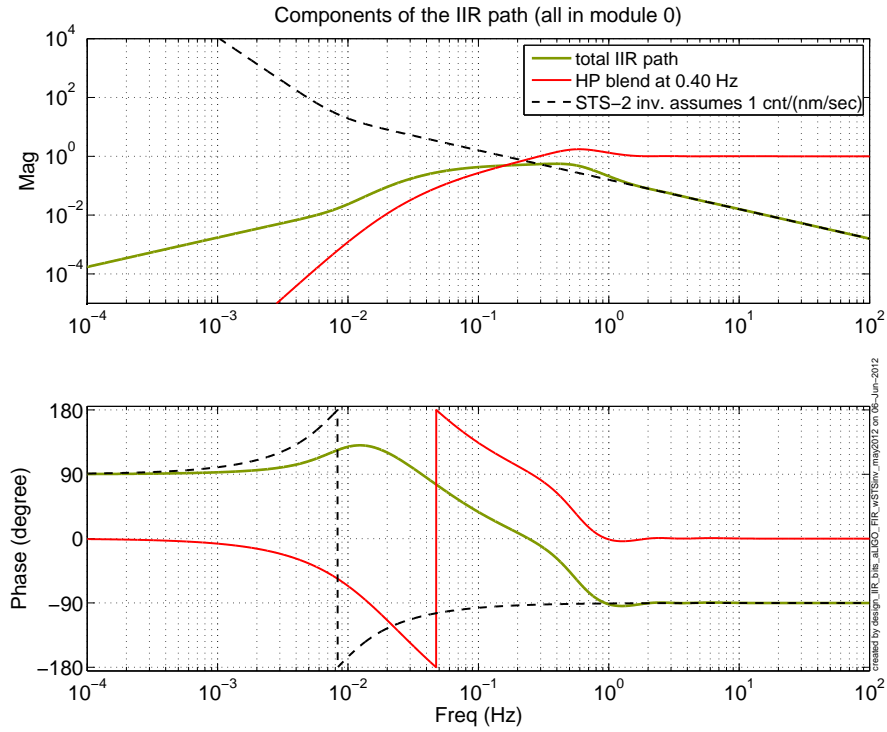
Figure 6: The IIR path. This filter converts the STS-2 into displacement and filters the resulting displacement signal with the highpass part of the 0.4 Hz blend filter.

2.4 Combined Paths

In figure 7 we can see the final transmission of the sensor correction filter. This is the sum of the FIR and IIR paths, and is also the product of the STS-2 sensor inversion and the final highpass filter from figure 2.
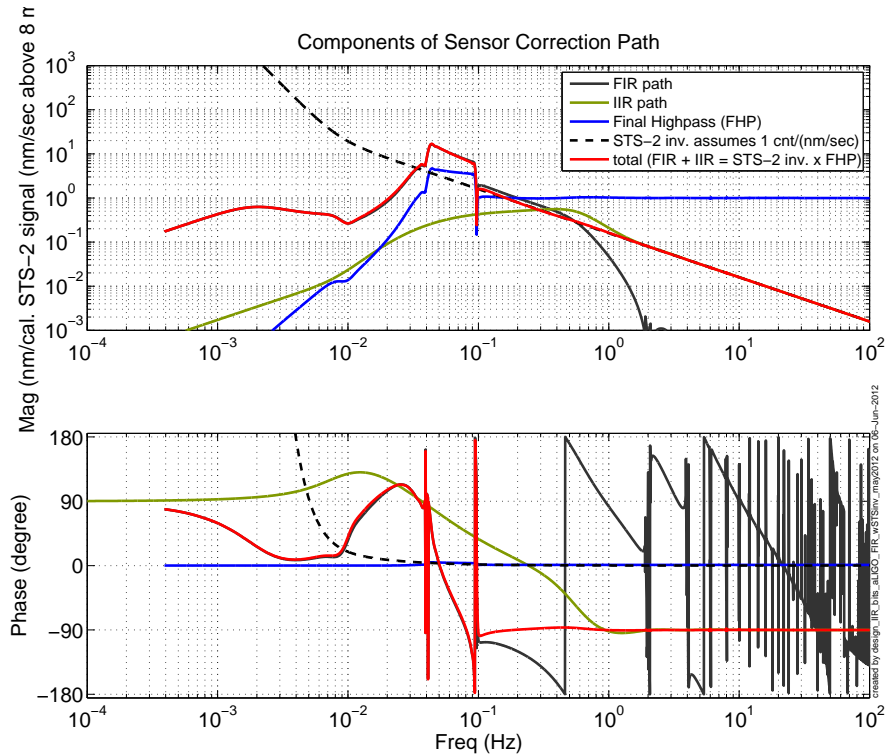
Figure 7: The final filter for sensor correction. This is the sum of the FIR and IIR paths. It is also the product of the STS-2 sensor inversion and the final highpass filter.

2.5 Final Performance Estimate and Matching

If we have properly calibrated the STS-2 and the CPS, and the transmission of ground motion to the HEPI structure is unity, then the performance of the sensor correction should be the difference between the final highpass filter and 1. It should be clear that changing the IIR filters will change the performance. In particular, small phase errors can easily cause performance changes. The performance estimate is shown below in figure 8. If the performance is not this good, there is a set of *matching filters* which can be used to try and compensate for the difference.
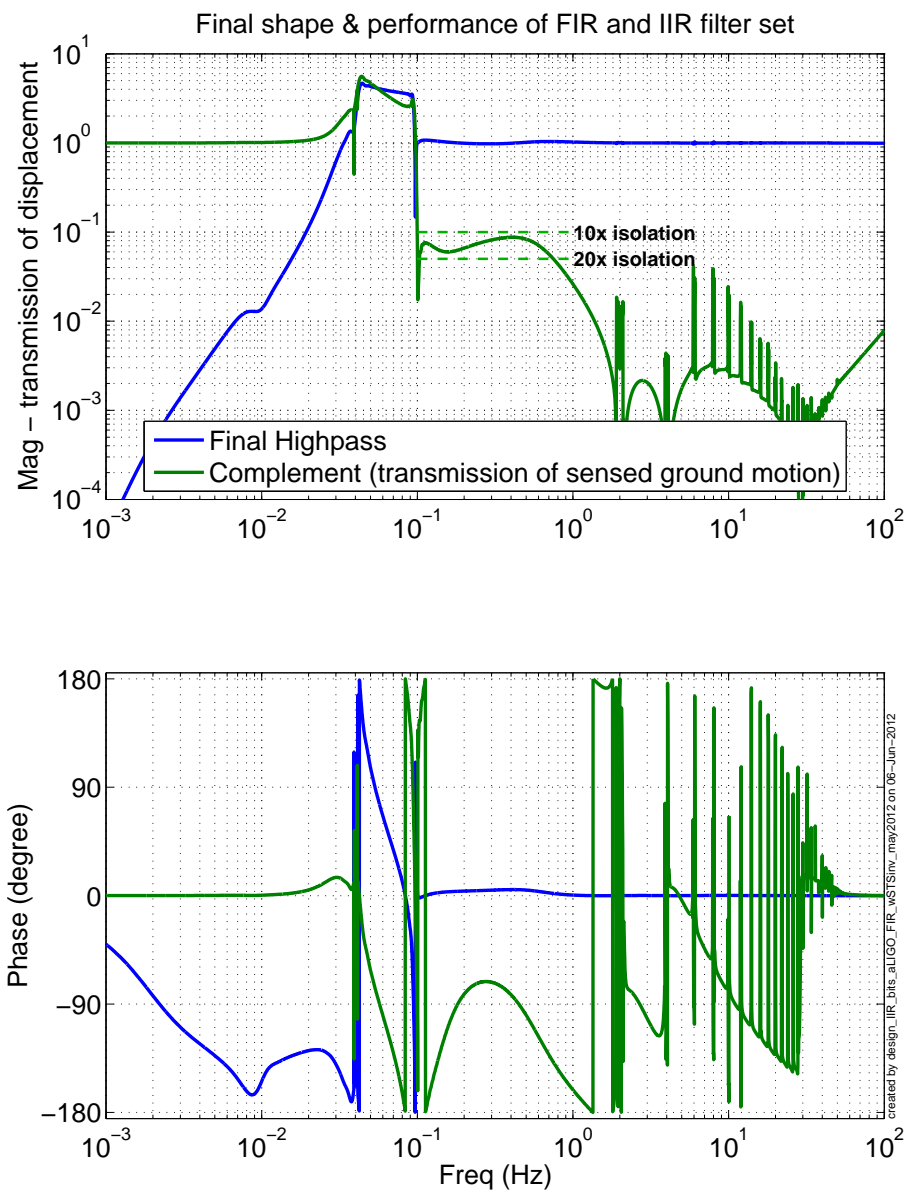
Figure 8: The final performance estimate for the sensor correction signals.

3 Implementation

The filter design tools are in the seismic SVN in the Common/MatlabTools/FIR_design/ folder, which is commonly available at `https://trac.ligo.caltech.edu/seismic/browser/Common/MatlabTools/FIR_design/`.

The driving script is design_IIR_bits_aLIGO_FIR_wSTSinv_may2012.m. This script makes plots and builds the data structure, using filters designed by the design function design_aLIGO_FIR_companion_filters_20120112.m.

The driving script creates a data structure called FIR_2k_filter_struct_2012_05_30 which is saved in the file HPI_2k_FIR_companion_filters_20120530.mat. This data file is in the FIR_tools folder, and also in the CDS userapps SVN in the trunk/hpi/common/filter-files/ directory. This directory also contains a generic version of the FIR filter, MAS-TER_FIR_FILE.fir.

These are designed to be put into the SENSCOR block of the HEPI diagram, in the modules

IFO:HPI-*CHAMBER*_SENSCOR_*DOF*_IIRHP and

IFO:HPI-*CHAMBER*_SENSCOR_*DOF*_FIR, e.g.

H1:HPI-ITMY_SENSCOR_X_FIR, or M1:HPI-HAMX_SENSCOR_Y_IIRHP

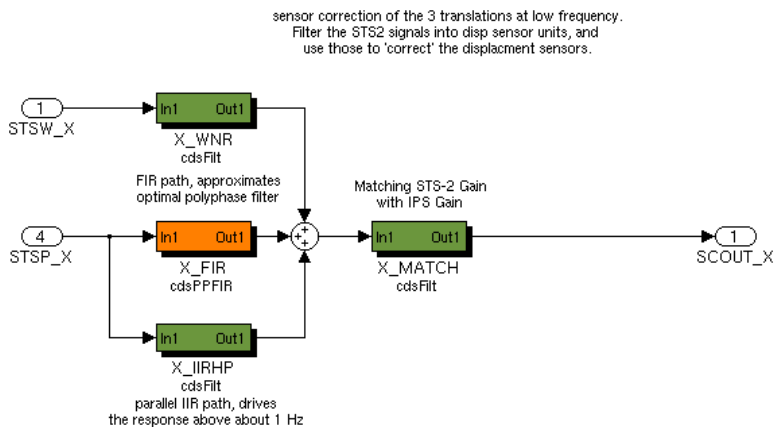A detail of the diagram is shown below in figure 9

Figure 9: Detail of the X signal path in the HEPI SENSCOR block, showing the parallel CDS control filters for the FIR and IIR paths. The MATCH filter follows the basic filtering and can be used to account for better gain matching or dynamics in the plant path, e.g. pier resonances. There is also a tie-in point for the weiner filtering.

An example of a script which could be used to install the FIR and companion IIR filters is shown below. This script installs the filters at Stanford (S1) for the HAMX chamber

(which doesn't really exist).

```matlab
% Script to load FIR and companion filters for HEPI sensor correction

%% Initialization
ifo = 'S1';
subsys = 'HPI';
chamber = 'HAMX';

model_name = [ifo,subsys,chamber];

[filenames, dcuid, found_files] = get_filenames(model_name, 'verbose');

userapps_path = '/opt/rtcds/userapps/cds_user_apps/trunk/';

%% Create FIR and companion filters

% create the FIR file
install_FIR_filter(model_name);

% add the IIR filters to the foton file
load([userapps_path,'hpi/common/filterfiles/',...
    'HPI_2k_FIR_companion_filters_20120530.mat']);
this_senscor_set = individualize(FIR_2k_filter_struct_2012_05_30, chamber);
autoquack(filenames.foton, this_senscor_set);
```