

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY  
- LIGO -  
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Technical Note	LIGO-T1100613-v3	2012/06/04
<b>Real-Time Band-Limited RMS Monitor</b>		
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We describe the implementation of a digital real-time band-limited RMS monitor. The necessary C code, matlab scripts, simulink parts, and medm screens are also documented.

We provide instructions to normalize the output of the filter to the Advanced LIGO requirement for a particular instrument.

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## 1 Introduction

To get a quick, accurate snapshot of the seismic platform's performance, it is useful to have a live monitor of the amount of activity in various frequency bands. We have implemented a digital real-time band-limited RMS filter to accomplish precisely this task. The lowpass and bandpass filters are 16th-order elliptical filters implemented as cascaded second-order sections using a direct form two digital filter. The RMS filter is implemented as a first-order digital low-pass filter with a decay time inversely proportional to the characteristic frequency of each band. The code has been written to support different sets of bands so that different sets of coefficients can be used in models with different rates. While there are a number of applications for this tool, we have used it to create a monitor of the RMS inertial motion of BSC Stage 2 in each band, normalized to the Advanced LIGO requirement for motion in that band.

## 2 C code

The digital filter was implemented in C to allow the code to be run on a front-end machine in real time. The full C code can be found in appendix A, and the file itself can be found in `userapps/release/cds/common/src/BLRMSFILTER.c`. While the code was initially developed independently, modifications for improved efficiency were taken from Embree [1, p. 128].

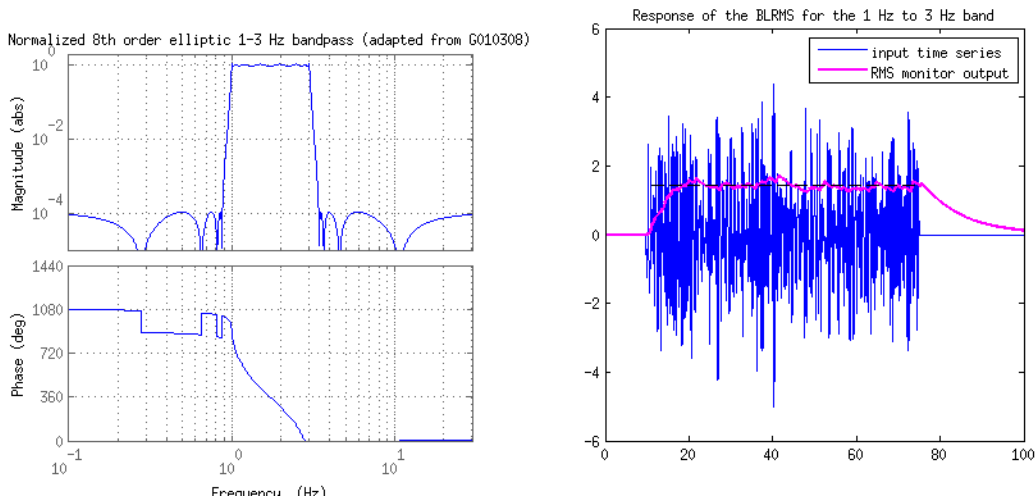


Figure 1: a. The bandpass filter for the 1 – 3 Hz band. b. The filter response to a uniform-power 1 – 3 Hz signal. The decay time of the rms filter for the 1 – 3 Hz band is 8 seconds. The code to generate this figure can be found in the Seismic svn at `/seismic/BSC-ISI/Stanford/slisi_tools/design_blrms/BLRMS_study2.m`.

We chose to implement the bandpass filters as cascaded second-order sections due to numerical accuracy problems associated with high-order filters. The coefficients for each second order section, as well as the gains for each band and the necessary RMS alpha coefficients are all hardcoded, since recalculation of new band limits is both computationally expensive

and mathematically difficult. If the values need to be changed, there is a matlab script that produces a formatted string that can be copy and pasted into the C file with the appropriate values for each set of coefficients (see section 3).

Different sets of bands are specified by providing a constant as a second input (via a MUX input in the simulink diagram) to the C code block. A constant of zero will get you a set of filters that have all zero coefficients. The first set of bands, specified by the constant 1, is for 4096 Hz models with the bands every half-decade from a low-pass at 100mHz to a band-pass from 30 Hz to 100 Hz. The second set is the same set of bands, but for 16 kHz models.

The filter was implemented as a direct form two digital filter, a good description of which can be found in Oppenheim and Schaffer [2, p. 389]. This implementation minimizes the number of delay registers needed to implement a filter, and thus is faster and more memory-efficient than direct form one (the noise associated with direct form two, for this application, is negligible). Constants to define the number of sets of bands, the number of bands in each set, and the number of second-order sections are at the top of the code.

In order to minimize the calculation time needed for this part, we decided to downsample the real-time signal using a moving average, and feed this moving average to a different band on each new input. This avoids calculating the rms value of each band on each loop, cutting computation time by nearly an order of magnitude. It is important to note that each band sees a slightly different timing window of the downsampled signal, though given that the bands of interest have frequencies well below the sampling rate, this should cause a negligible difference.

### 3 Matlab scripts

We wrote a matlab script to automate the generation of second-order-section coefficients for each frequency band. The full script can be found in appendix B and at `SeismicSVN/seismic-/BSC-ISI/Stanford/s1isi_tools/design_BLRMS/sos_coeffs.m`. The first section of the script defines all of the relevant variables that are used during the calculation of the different filter coefficients. The sampling time is not the real-time rate, but rather the downsampled input to the filter itself.

The lowpass filter is implemented as a 16th order elliptical filter that is normalized to have a value of 1 at DC (hence the factor of  $10^{\frac{1}{20}}$ ). In order to prevent numerical errors that result from simply calling `c2d` on the continuous version of the filter, we first convert to state space, then take `c2d`, then convert that to `zpk` form. Each bandpass filter is implemented as an 8th order bandpass filter (really 16th order) and scaled such that the mean value of the filter within the band is normalized to one. This results in a scaling factor of 1.0591. It is important to note that the two highest frequency bands do not fit precisely with the pattern that the others follow. This is due to the fact that the conversion to a digital filter warps the higher frequencies down, since they are relatively closer to the Nyquist frequency (256 Hz in this case). The upper frequencies were corrected manually to have the values 30.3 Hz and 115 Hz such that these limits actually mapped to 30 Hz and 100 Hz respectively.

The time constants for the rms filter were calculated by scaling the inverse of the geometric

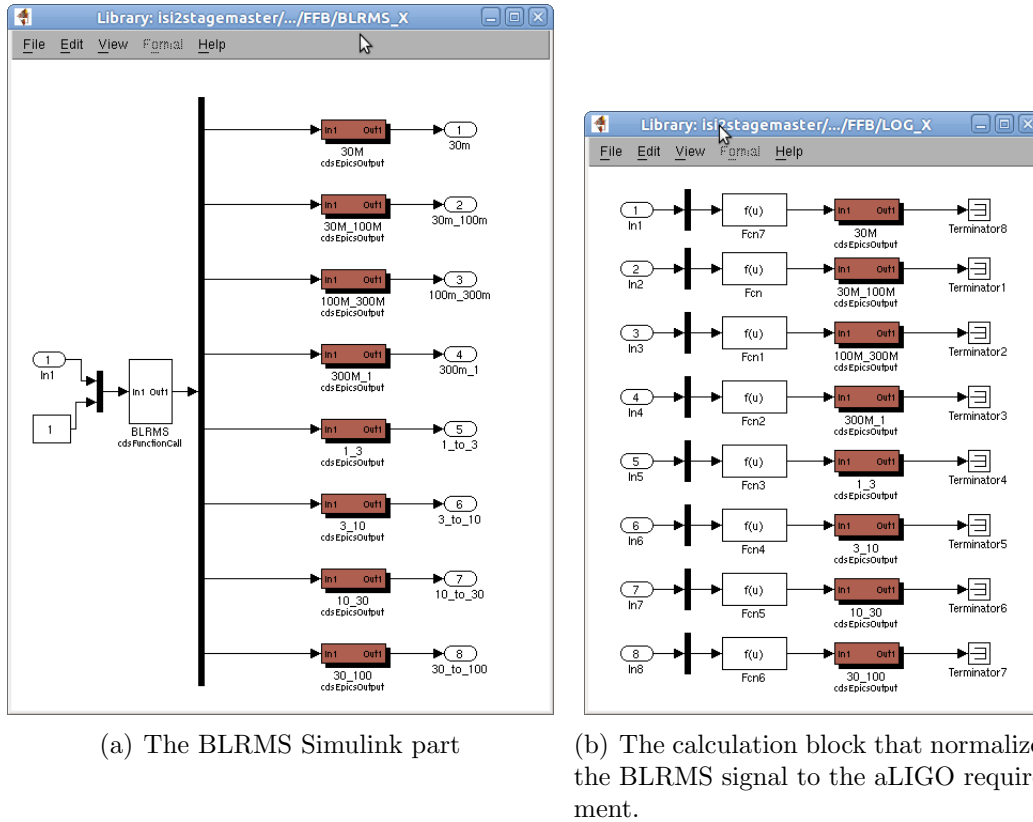


Figure 2: These screenshots show the BLRMS C code diagram and the normalization diagram in simulink.

mean of each frequency band by eight, which was a number determined experimentally to have a desirable mix of quick response time with a sufficient degree of accuracy. The time constants, the coefficients for the second order sections, the gain values for each filter, and the rms alpha coefficients are each outputted in a format conducive to copying and pasting into the C code so that the limits of each band can be customized quickly by the user.

## 4 Simulink part

A simulink part (Figure 2(a)) has been created that outputs the band-limited rms value for each frequency band as EPICS values. When this part is placed in the model, it creates eight EPICS output variables corresponding to the eight different bands. The bands are labelled by their corresponding frequencies, e.g. the low-pass has the label BLRMS\_30M, the microseismic band has the label BLRMS\_30M\_100M, and so on. This part then passes these values as outputs to the outside of the block should the user want to do any further calculations.

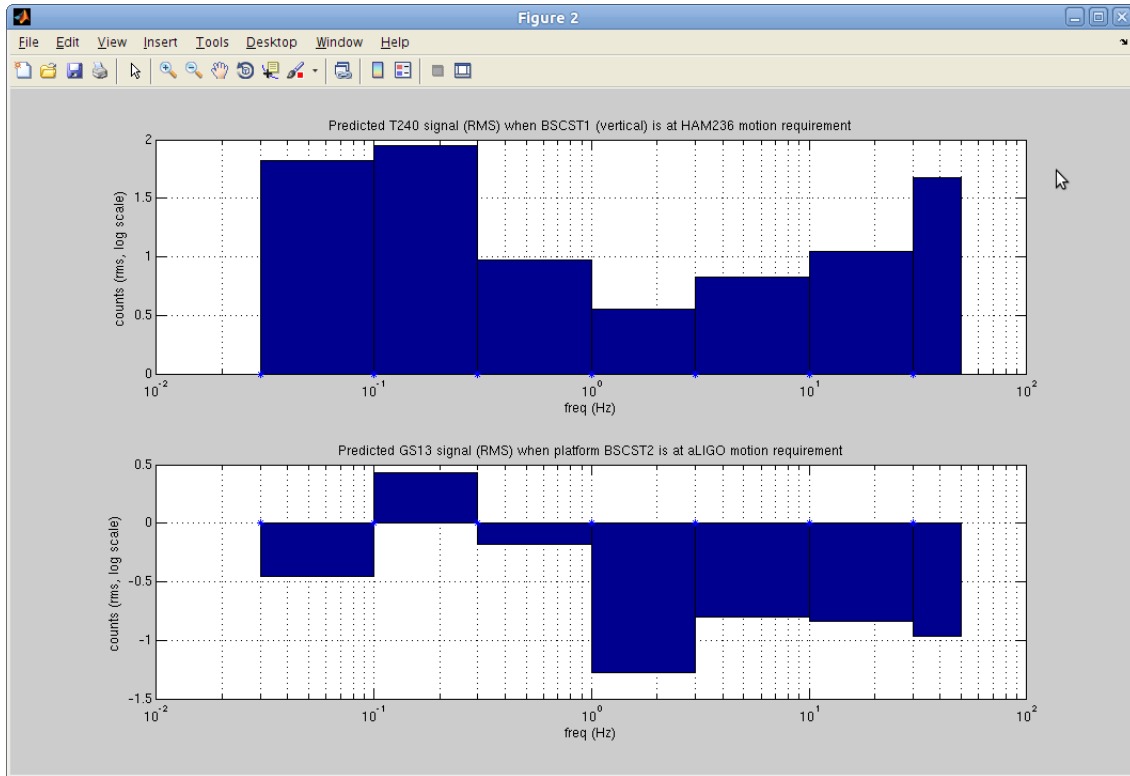


Figure 3: The expected RMS signal (log scale) from the Stage 1 T240s (left) and Stage 2 GS13s (right) when the platform is operating at the aLIGO BSC motion requirement.

#### 4.1 Normalization to the Advanced LIGO requirement

One of the possible uses for this part is to determine how well the platform is performing with respect to the Advanced LIGO requirement. A script for calculating the RMS signal from

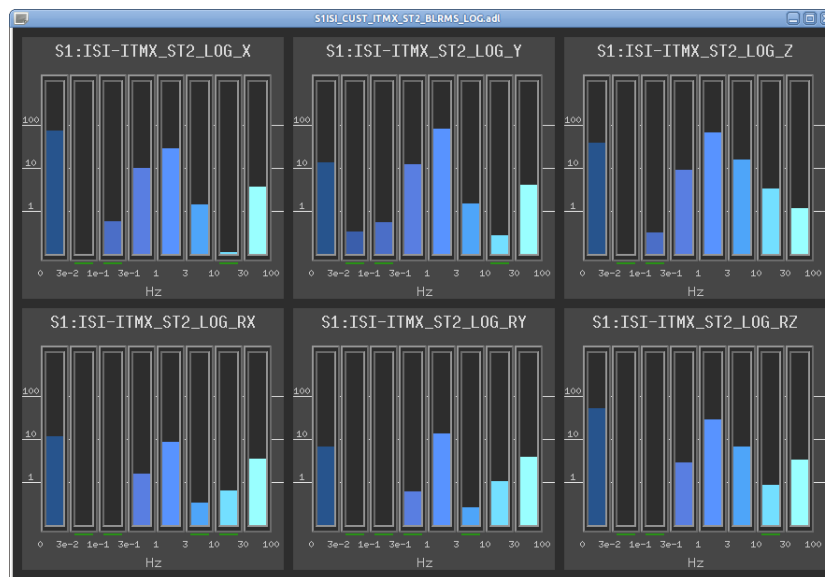


Figure 4: A monitor of the activity in the stage 2 GS13, plotted on a log scale normalized to the advanced LIGO requirement.

the stage two GS13 at the BSC requirement is attached in appendix C and can be found in `SeismicSVN/seismic/BSC-ISI/Stanford/s1isi_tools/design_BLRMS/GS13_signals_onBSC.m`. We calculate the expected signal by integrating the ASD in each frequency band, estimating DC as  $0.00001 Hz$ . The results are plotted in Figure ??.

After calculating the values, we can use them to display the RMS activity in each band on a log scale normalized to the requirement. Such a display makes comparisons between the activity in different bands possible. Figure 4 shows such a comparison.

## 5 MEDM

The previous section referenced Figure 4, which is an medm screen that plots the RMS signal in each band normalized to its expected value when the system is operating at the BSC requirement. A version of this screen has been prepared with macro-substitution and can be found in `userapps/release/isi/common/medm/ISI_CUST_CHAMBER_BLRMS_LOG.ad1`.

## References

- [1] Paul M. Embree. *C Algorithms for Real-Time DSP*. Prentice Hall, Upper Saddle River, NJ, 1995.
- [2] Alan V. Oppenheim and Ronald W. Schaffer. *Discrete-Time Signal Processing*. Prentice Hall, Upper Saddle River, NJ, third edition, 2010.

## A BLRMSFILTER.c

Note that lines 37-90 have been omitted since they are simply the coefficients for each second order section.

```

/* switchblrms.c
 *
 * This function implements a band-limited rms filter
 * The bandpass filter is implemented as a discrete direct form 2 filter.
5  *
 * Authors: CJK BTL
 * January 6 2012
 *
 * Documentation available in DCC document T1100613.
10 */

#define NUMBANDS 8
#define NUMSOS 8 // number of SOS (defined by order * 2)
#define NUMCOEFFS 4 // number of coefficients (since b0 = a0 = 1, can just
15 #define NUMBAND_OPTIONS 5 // number of different sets of bands, including
    default zeroes bands

/* SET 0: Zeroes.
 *
 * SET 1: For models w/ datarate of 4096
20 * The bands are a lowpass with a corner frequency of 0.03 Hz, then bandpass
    filters with frequencies
 * every half-decade from 0.03Hz to 100Hz, e.g. 1Hz - 3Hz, 3Hz-10Hz, etc.
 *
 * SET 2: For models w/ datarate of 16384
 * Same as bands for set 1.
25 *
 * SET 3: For models /w datarate of 16384
 * The bands are a lowpass with a corner frequency of 0.03 Hz, then bandpass
    filters with frequencies
 * every half-decade from 0.03Hz to 10Hz, e.g. 1Hz - 3Hz, 3Hz-10Hz, then from
    10-50Hz and 50Hz-500Hz
 *
30 * SET 4: For models w/ datarate of 2048 (HEPI)
 * Same bands as set 1, except last band is a high-pass with a corner
    frequency of 30 Hz
 */
static double sos_coeffs [NUMBAND_OPTIONS] [NUMBANDS] [NUMSOS] [NUMCOEFFS] =
35 {
{
{{0.0, 0.0, 0.0, 0.0},
{0.0, 0.0, 0.0, 0.0}},
{{0.0, 0.0, 0.0, 0.0},
{0.0, 0.0, 0.0, 0.0},
{0.0, 0.0, 0.0, 0.0},
{0.0, 0.0, 0.0, 0.0},

```

BLRMSFILTER.c

```

90 {0.0, 0.0, 0.0, 0.0},
{0.0, 0.0, 0.0, 0.0}},
{{0.0, 0.0, 0.0, 0.0},
{0.0, 0.0, 0.0, 0.0},
{0.0, 0.0, 0.0, 0.0},
{0.0, 0.0, 0.0, 0.0},

```



```

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    {0.0, 0.0, 0.0, 0.0},
    {0.0, 0.0, 0.0, 0.0},
    {0.0, 0.0, 0.0, 0.0}}
100 },
    //SET 1
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      +0.999901776607053},
105  {-1.999999785867503, +0.999999999998477, -1.999947274295583,
      +0.999947364551760},
    {-1.999999835315568, +0.999999999901861, -1.999975330616235,
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    {-1.999999842979189, +0.999999984060132, -1.999995768834058,
      +0.999995901243379},
    {-1.999999899847953, +1.000000038365326, -1.999997234862473,
      +0.999997369601408},
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      { -1.500979461688740, +1.000000088597731, -1.493620818059611,
      +0.999154994109446}}
    }
  };
370 // The overall gain for each band
static double g[NUMBAND_OPTIONS][NUMBANDS] =
{
{0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0},
375 {0.000112183165792, 0.000105869013273, 0.000105796356279, 0.000105558685102,
      0.000105248093676, 0.000108075052843, 0.000145444643508,
      0.00111268350408}, // Set 1
{0.000112197156751, 0.000105899630900, 0.000105880590539, 0.000105809979638,
      0.000105645813872, 0.000105273600293, 0.000106242311402,
      0.00014984827880}, // Set 2
{0.000112197156751, 0.000105899630900, 0.000105880590539, 0.000105809979638,
      0.000105645813872, 0.000105273600293, 0.000112773780492,
      0.00296961827569}, // Set 3
{0.000112164686402, 0.000105829331565, 0.000105693343841, 0.000105336599667,
      0.000105622097453, 0.000122409832774, 0.000304523250745,
      0.10925941222306} // Set 4
};
380 // The rms coefficients that determine the time constant for the rms
      filter,,,,,,,,,
static double rms_coeffs[NUMBAND_OPTIONS][NUMBANDS] =
{
{0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0},
385 {0.000007324165106, 0.000013371953940, 0.000042284608605, 0.000133703448513,
      0.000422685228339, 0.001335427523746, 0.001949317738791,

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```

    0.00194931773879}, // Set 1
{0.000001831051335, 0.000003343022012, 0.000010571487410, 0.000033429214329,
  0.000105704816983, 0.000334191597430, 0.000488042947779,
  0.00048804294777}, // Set 2
{0.000001831051335, 0.000003343022012, 0.000010571487410, 0.000033429214329,
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  0.00048804294777}, // Set 3
{0.000014648222926, 0.000026743550267, 0.000084565641386, 0.000267371148582,
  0.000845013282047, 0.002667293070912, 0.003891050583658,
  0.00389105058365} // Set 4
};
390
/* This function implements a real-time band-limited rms filter using
 * direct form two real-time filter implementation for the band filtering ,
 * and a simple low-pass filter for the rms filtering.
 * argin has two inputs: the first is the real-time value, the second is the
   number
395 * corresponding to which set of band limits to use.
 * argout has eight outputs for each band
 */
void BLRMS(double *argin, int nargin, double *argout, int nargs){
  // GLOBALS
400  static int band = 0; // Current band being
   calculated
  static double cur_avg = 0; // Input downsampled by a factor of 8
  static double prev_rt_input [NUMBANDS]; // array containing
   previous rt input
  static double w_hist [NUMBANDS][NUMSOS][2]; // 3D array containing
   history of inputs for w
  static double rms [NUMBANDS]; // Array containing the rms values
405  static double ms [NUMBANDS]; // Array containing ms values to speed up
   computation

  int ii = 0;
  int set = (int)*(argin + 1) % NUMBAND_OPTIONS;
  // Calculate the new input as an average of the previous NUMSAMPLES samples
410  double cur_rt_input = *argin;
  int prev_band = (band + (NUMBANDS) - 1) % (NUMBANDS);
  cur_avg = cur_avg - (prev_rt_input [band] - cur_rt_input) / NUMBANDS;
  prev_rt_input [band] = cur_rt_input;

415  // Declare the variables we'll need below to speed up allocation
  double new_input = cur_avg, new_output = 0;
  double hist1, hist2, new_w, a1, a2, b1, b2;
  double *hist1_ptr = &w_hist [band][0][0], *hist2_ptr = &w_hist [band][0][1],
   *coeff_ptr = &sos_coeffs [set][band][0][0];
  for(ii = 0; ii < NUMSOS; ii++){
420  // Get the previous history values
   hist1 = *hist1_ptr;
   hist2 = *hist2_ptr;

   // Get the coefficients from the coefficient matrix
425  b1 = *coeff_ptr++;
  b2 = *coeff_ptr++;
  a1 = *coeff_ptr++;
  a2 = *coeff_ptr++;

```

```
430 // Calculate the new w, and then the new output
new_w = new_input - a1 * hist1 - a2 * hist2;
new_output = new_w + b1 * hist1 + b2 * hist2;

// Shift the histories and increment the history pointers
435 *hist2_ptr++ = hist1; ++hist2_ptr;
*hist1_ptr++ = new_w; ++hist1_ptr;

// Push the output down the line of sections
new_input = new_output;
440 }
// Calculate the rms output
new_output = new_output * g[set][band];
double ms_val = ms[band], rms_coeff = rms_coeffs[set][band];
ms_val = new_output * new_output * rms_coeff + ms_val * (1 - rms_coeff);
445 rms[band] = sqrt(ms_val);
ms[band] = ms_val;

// Increment or reset the band number
if(++band >= NUMBANDS) { band = 0; }
450

// Write to the output array
double *rmsptr = &rms[0];
for(ii = 0; ii < NUMBANDS; ++ii){
    *argout++ = *rmsptr++;
455 }
}
```

BLRMSFILTER.c

**B sos\_coeffs.m**

```

%% SOS Coefficients for real-time BLRMS monitor
% updated by BTL on Nov 9, 2011 to simplify the conversion to discrete time
% clear all, close all;

5 %% General settings
format long;
Ts = 1/512; % sample time
order = 8; % elliptical filter order
ripple = 1; % 1db of ripple
10 atten = 80; % 80db of attenuation
corner = 0.030; % low pass corner frequency
frequencies = [0.03, 0.1, 0.3, 1, 3, 10, 30.3, 115]; % frequency band limits

%% Lowpass filter coefficients
15 [num den] = ellip(order*2, ripple, atten, 2*pi*corner, 'low', 's');
ellip_tf_c = 10^(1/20) * tf(num,den); % normalize to 1
ellip_zpk_d = zpk(c2d(ss(ellip_tf_c),Ts, 'tustin'));

20 %figure
%bode(ellip_tf_c, ellip_zpk_d);
%step(ellip_tf_c, ellip_zpk_d);

[zz, pp, kk] = zpkdata(ellip_zpk_d);
25 [low_sos, low_g] = zp2sos(zz{:}, pp{:}, kk);
full_sos{1}.sos = low_sos;
full_sos{1}.gain = low_g;

30 %% Bandpass filter coefficients

for x = 1:length(frequencies) - 1
    lower = frequencies(x);
    upper = frequencies(x+1);
35 [num den] = ellip(order, ripple, atten, [2*pi*lower,
        2*pi*upper], 'bandpass', 's');
    ellip_tf_c = tf(num,den);
    ellip_zpk_d = zpk(c2d(ss(ellip_tf_c),Ts, 'tustin'));

    %figure
40 %bode(ellip_tf_c, ellip_zpk_d);
%step(ellip_tf_c, ellip_zpk_d);

    [zz, pp, kk] = zpkdata(ellip_zpk_d);

45 [sos, g] = zp2sos(zz{:}, pp{:}, kk);
full_sos{x+1}.sos = sos;
full_sos{x+1}.gain = 1.0591 * g;
end

50 %% RMS coefficients
alpha = zeros(1,8); % actual coefficients
tau = zeros(1,8); % decay time constants
tau(1) = 8 / frequencies(1); % ~50/(2*pi) / geometric mean freq

```

```

alpha(1) = Ts / (Ts + tau(1));
55 for x = 1:length(frequencies)-1
    tau(x+1) = max(1, 8 / sqrt(frequencies(x) * frequencies(x+1)));
    alpha(x+1) = Ts / (Ts + tau(x+1));
end

60 %% write to a text file that we can just copy into C
coefficients = '';
gains = '{}';
alphas = '{}';
taus = '{}';
65
for k=1:length(frequencies)
    for j=1:order
        coefficients = [coefficients; sprintf('_%.15f, %.15f, %.15f, %.15f, %.15f, %.15f', ...
70             full_sos{k}.sos(j,2:3), full_sos{k}.sos(j,5:6))];
    end
    coefficients(order*(k-1) + 1, 1) = '{}';
    coefficients(order*k, end-2:end-1) = '{}';
    gains = strcat(gains, sprintf('_%.15f, ', full_sos{k}.gain));
    alphas = strcat(alphas, sprintf('_%.15f, ', alpha(k)));
75    taus = strcat(taus, sprintf('_%.15f, ', tau(k)));
end
coefficients(end, end-1) = '_';
gains(end, end-1:end) = '};';
alphas(end, end-1:end) = '};';
80
taus
coefficients
gains
alphas
85
%% plotting data (temp)
%{
blrms = importdata('blrms_test.txt');
x_axis = 0:1/4096:(length(blrms.data)-1)/4096;
90 figure;
plot(x_axis, blrms.data);
legend(blrms.colheaders)
%}

```

sos\_coeffs.m

**C normalize\_BLRMS\_filter.m**

```

% estimates of the signal from the GS13 when the BSC-ISI is at the req's

clear
close all
5
%%
freq = logspace(-2,3,10000);
good_vibrations = BSC_req(freq);

10 figure
loglog(freq, good_vibrations)
title('BSC_motion_spec')
xlabel('freq (Hz)')
ylabel('motion ASD (m/rtHz)')
15 grid on

% counts per meter per second for the calibrated GS13s
GS13_resp = 1e9 * tf('s') * zpk([0 0], -2*pi*[1+1i, 1-1i]/sqrt(2), (2*pi*1)^2);

20 figure
bode(GS13_resp)
title('GS-13_resp, in counts/meter/sec')

25 GS13_resp_FR = squeeze(freqresp(GS13_resp, 2*pi*freq)).';

GS13_signal = abs(GS13_resp_FR .* good_vibrations);

figure
30 loglog(freq, GS13_signal)
title('GS13_signal (ASD) when at BSC motion requirement')
xlabel('freq (Hz)')
ylabel('counts/rtHz')
grid on
35
%%

frequencies = logspace(-2,3,10000); %[0.00001 0.03 0.1 0.3 1 3 10 30 100];
rms_vec = zeros(1,8);
40 for i=1:length(frequencies)-1
    rms = intRMS_Band(GS13_signal, freq, frequencies(i), frequencies(i+1));
    rms_vec(i) = rms;
    sprintf('The rms requirement from %.2f to %.2f is %.3f.', frequencies(i),
            frequencies(i+1), rms);
end
45 rms_vec';
log10(rms_vec)';

figure
50 loglog(frequencies(2:end), rms_vec)
grid on
title('GS13_signal (RMS) when at BSC motion requirement')
xlabel('freq (Hz)')

```

`ylabel('counts')`

GS13\_signals\_onBSC.m